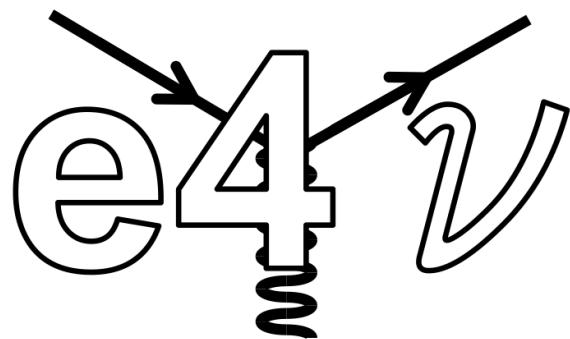


Electron-scattering constraints for neutrino-nucleus interactions

Lawrence Weinstein
Old Dominion University
NUSTEC 2019



Collaboration

- Old Dominion University
- MIT
- Jefferson Lab
- Tel Aviv U
- Michigan State
- FermiLab
- Pitt
- York University, UK



Mariana Khachtryan
(ODU)



Afroditi Papdopolou
(MIT)



Adi Ashkenazi
(MIT)



Florian Hauenstein
(ODU)

+ Minerba Betancourt (FNAL)

L. Weinstein, NUSTEC 2019

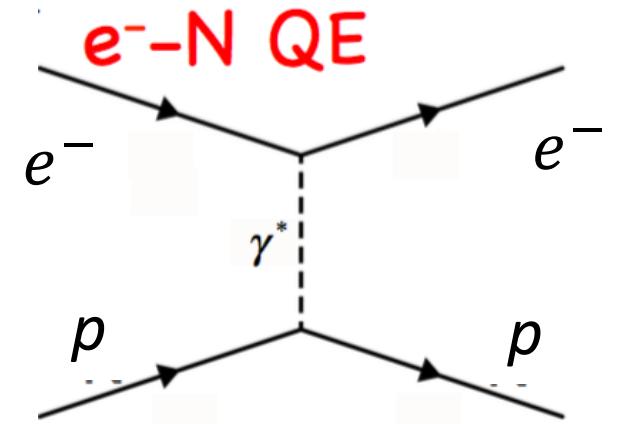
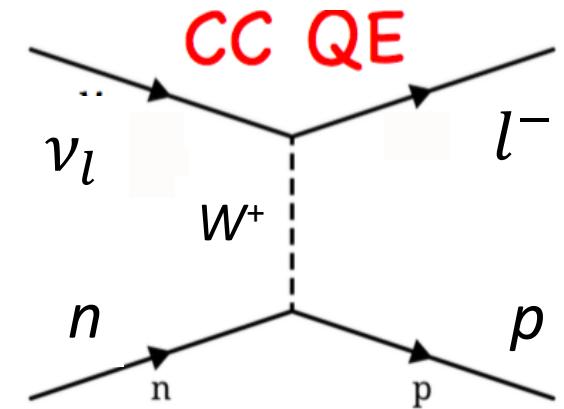
+ Lucas Tracy (ODU)

Outline

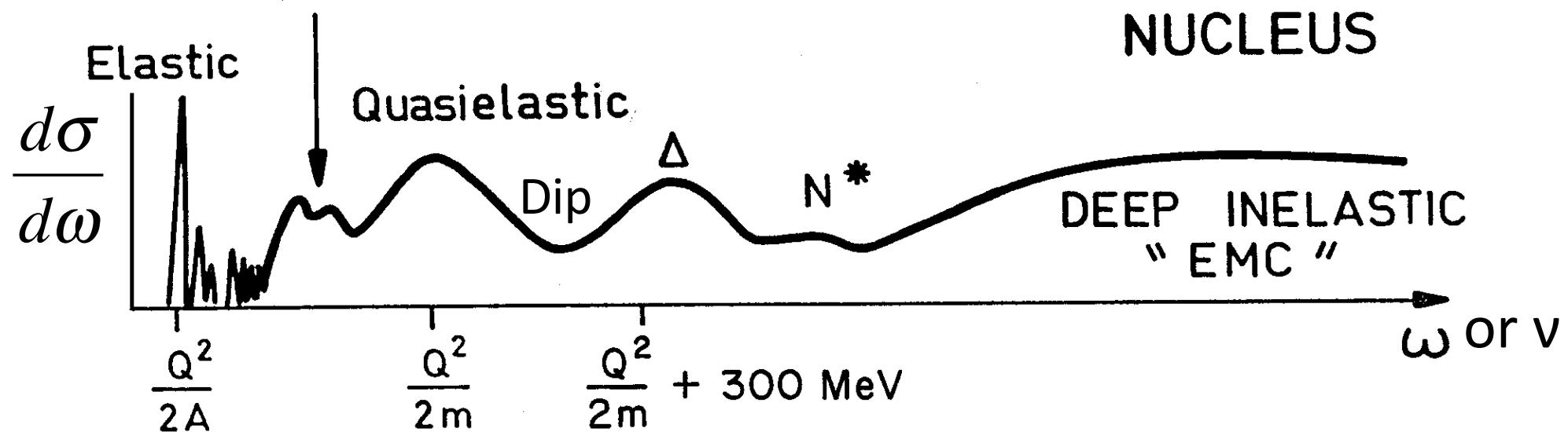
- Why electrons?
 - Nuclear Physics
- Current work
 - Zero pion channel (updated)
 - One pion channel (new)
- Future plans

Why electrons?

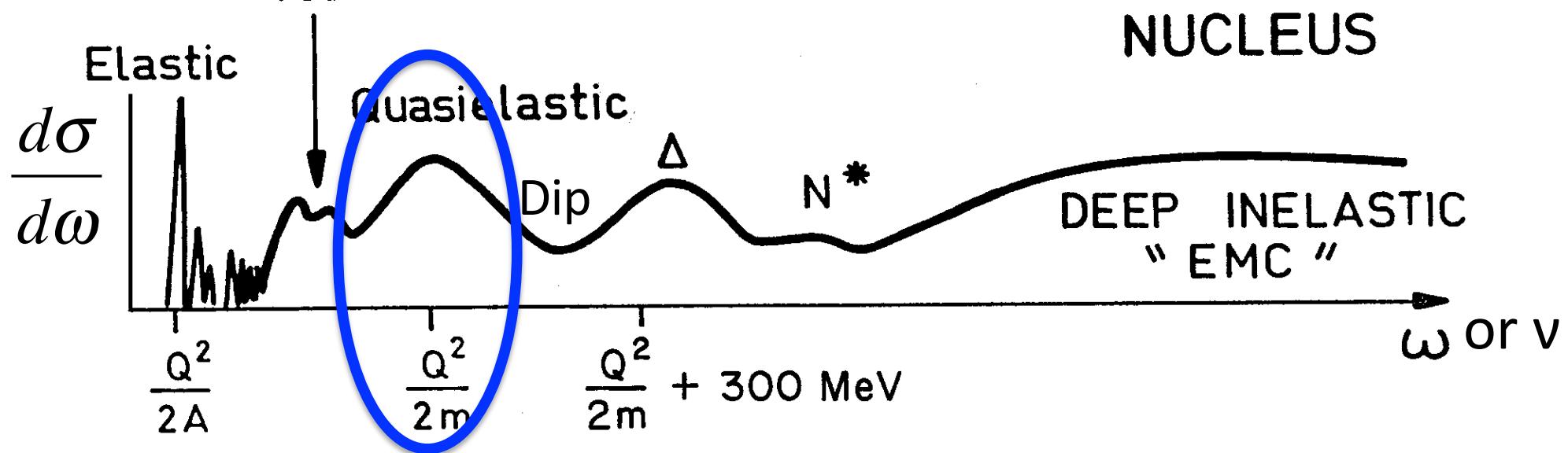
- Known incident energy
- High intensity
- Similar interaction with nuclei
 - Single boson exchange
 - CC Weak current [vector plus axial]
 - $j_\mu^\pm = \bar{u} \frac{-ig_W}{2\sqrt{2}} (\gamma^\mu - \gamma^\mu \gamma^5) u$
 - EM current [vector]
 - $j_\mu^{em} = \bar{u} \gamma^\mu u$
 - Similar nuclear physics



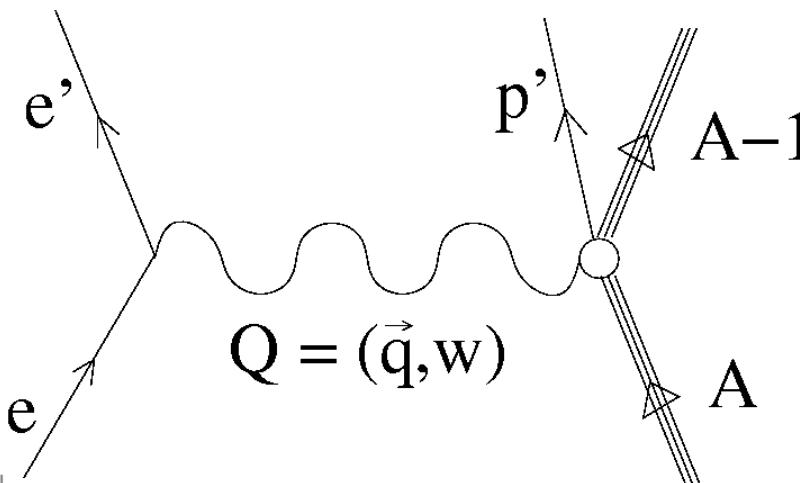
Nuclear Physics



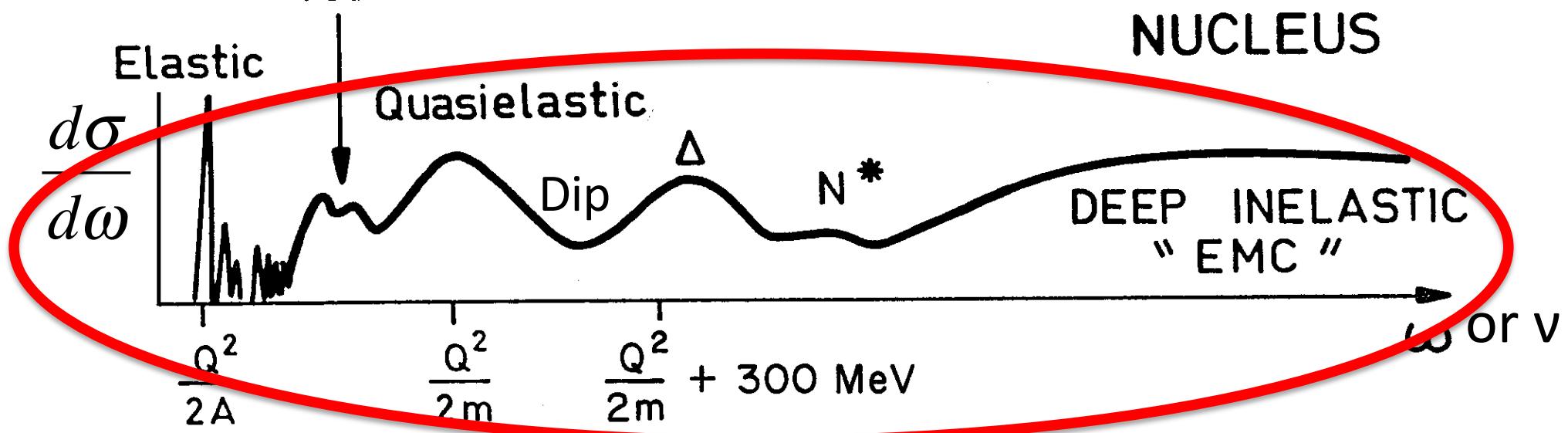
Nuclear Physics



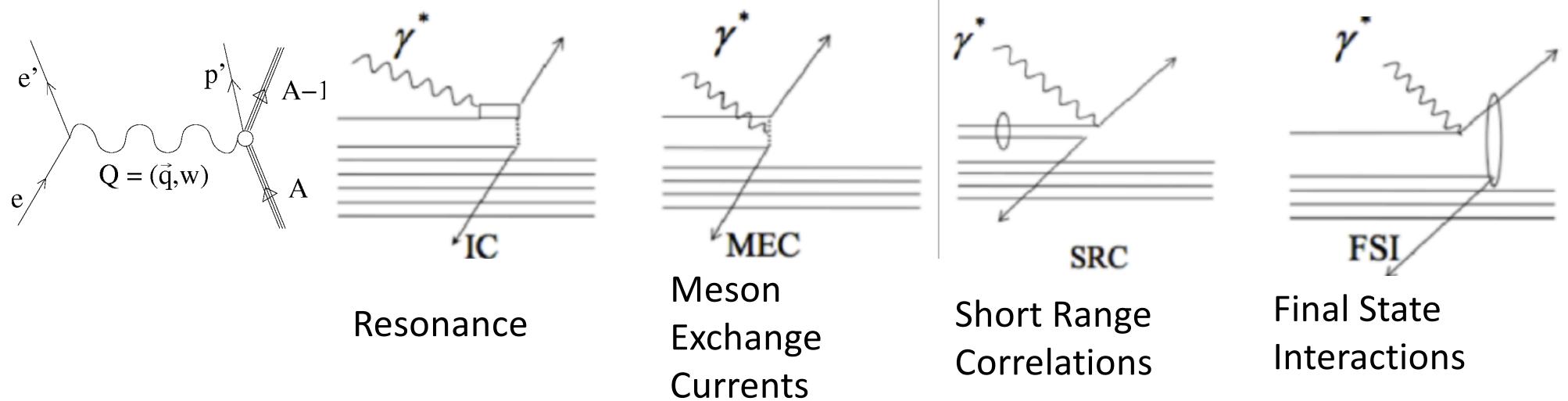
What neutrino expts want



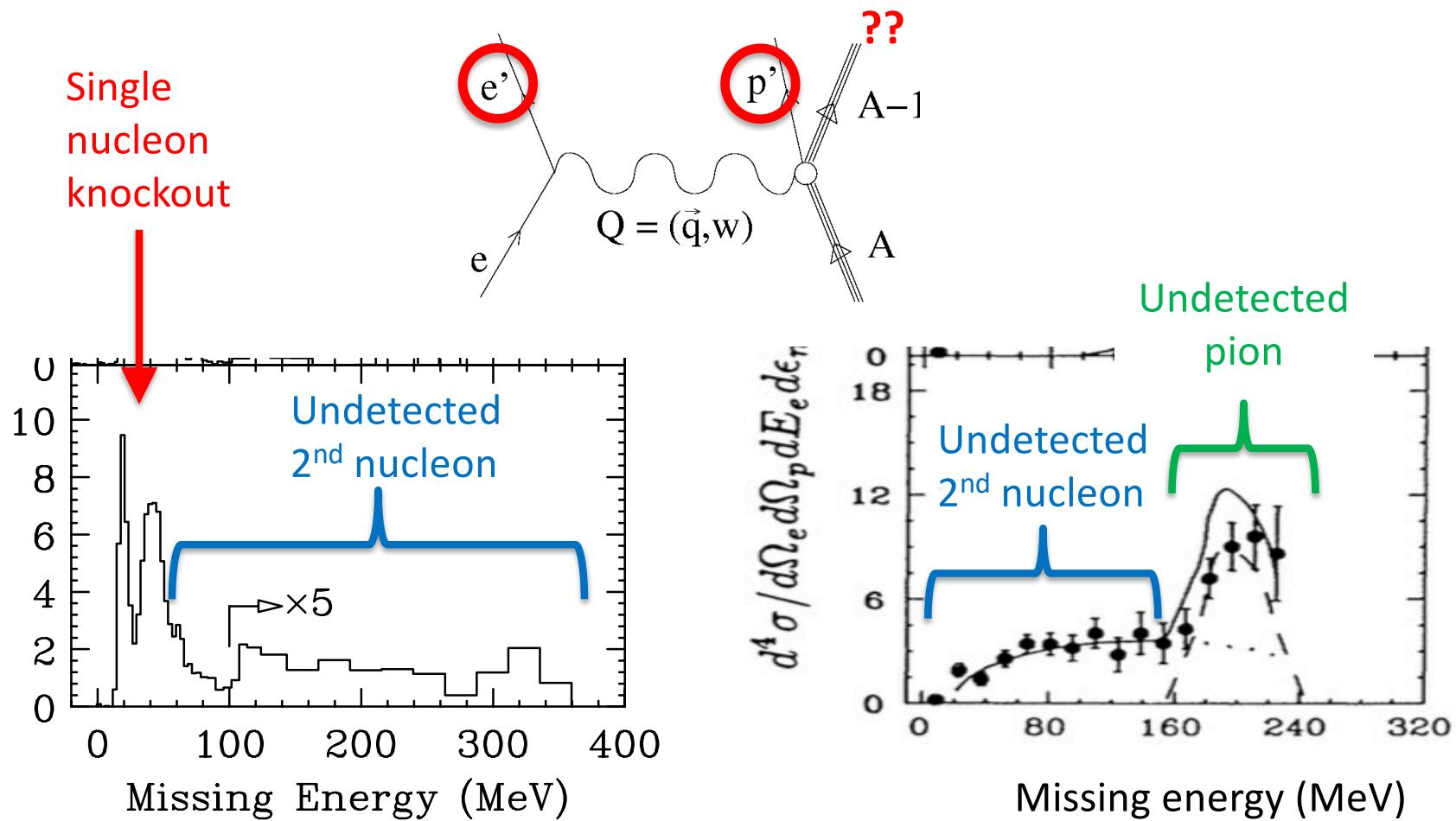
Nuclear Physics



What we get (even for 0pi)

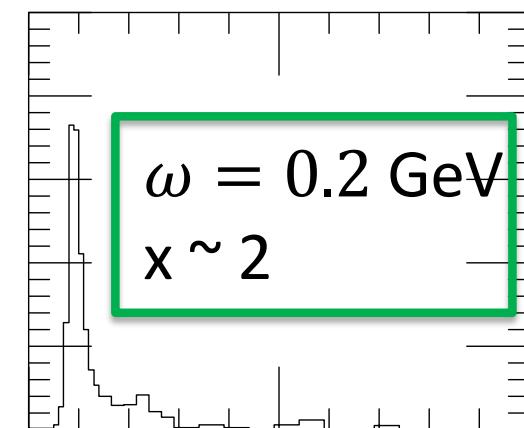


How do reaction mechanisms appear in $A(e, e' p)$?

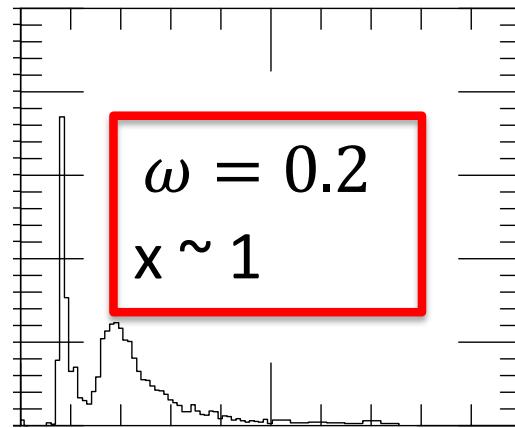


From QE to “dip”

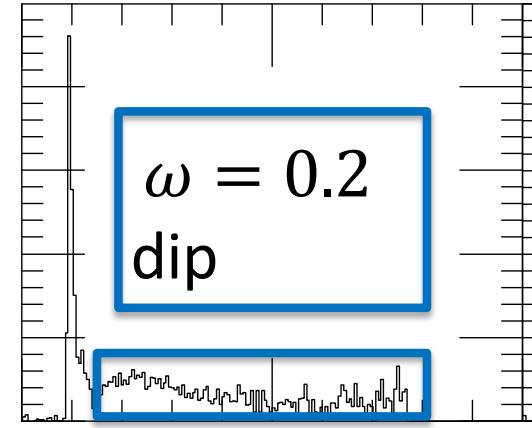
$C(e,e'p)$



0 100

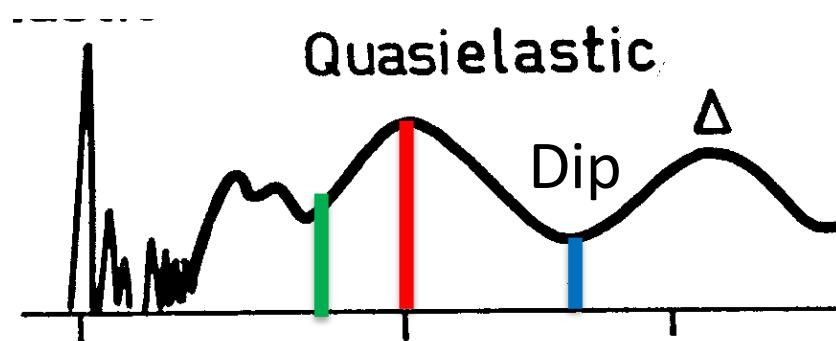


0 100



0 100

Missing energy [MeV]

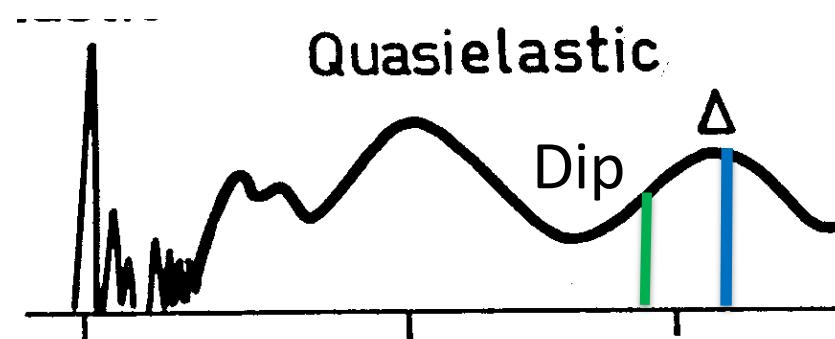
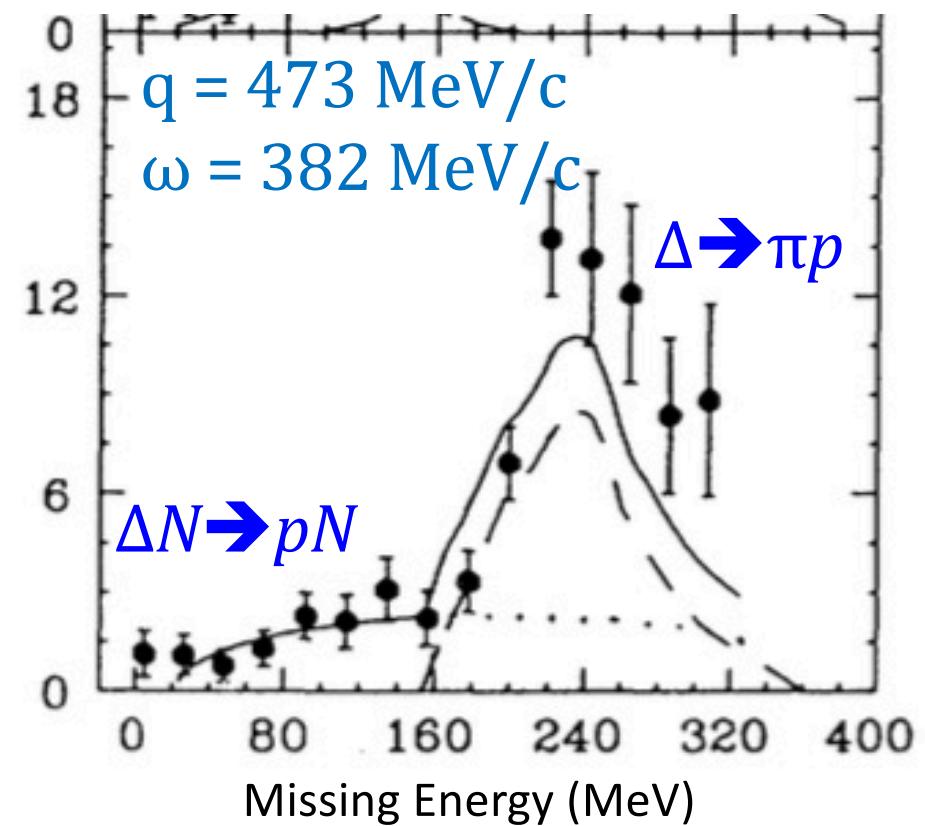
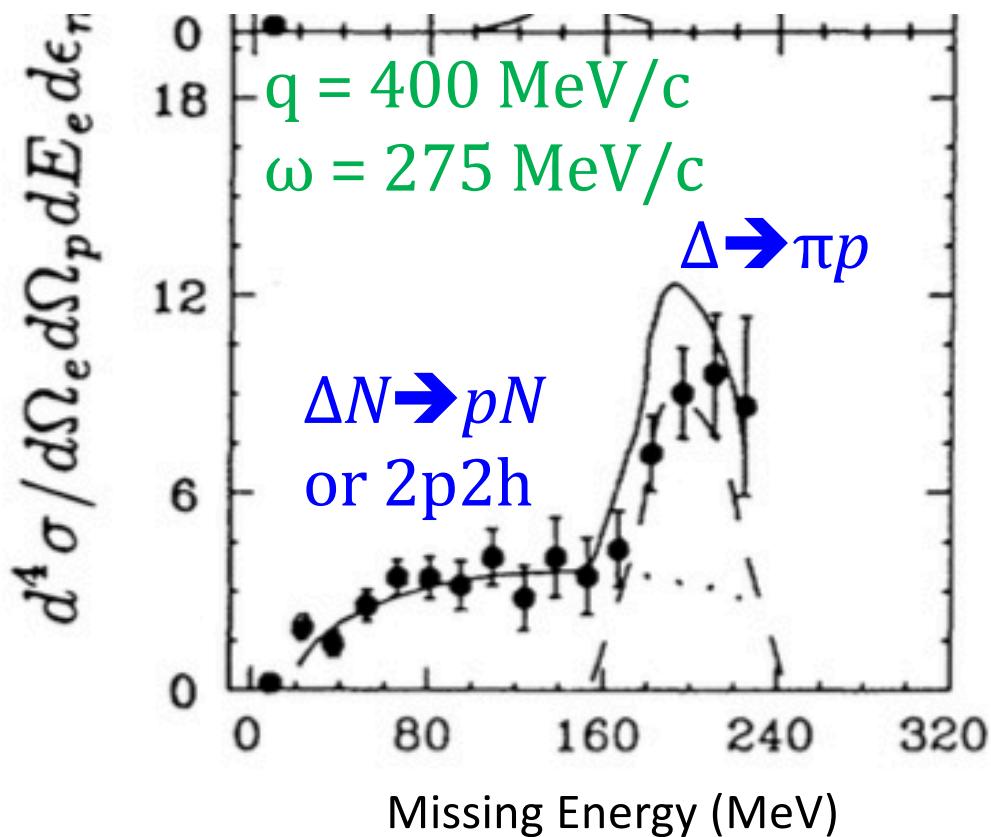


$$x = \frac{Q^2}{2m\omega}$$

R. Lourie, PRL 56, 2364 (1986)
 L. Weinstein, PRL 64, 1646 (1990)
 S. Penn, PhD thesis, MIT

$C(e,e'p)$

From Dip to Delta Region

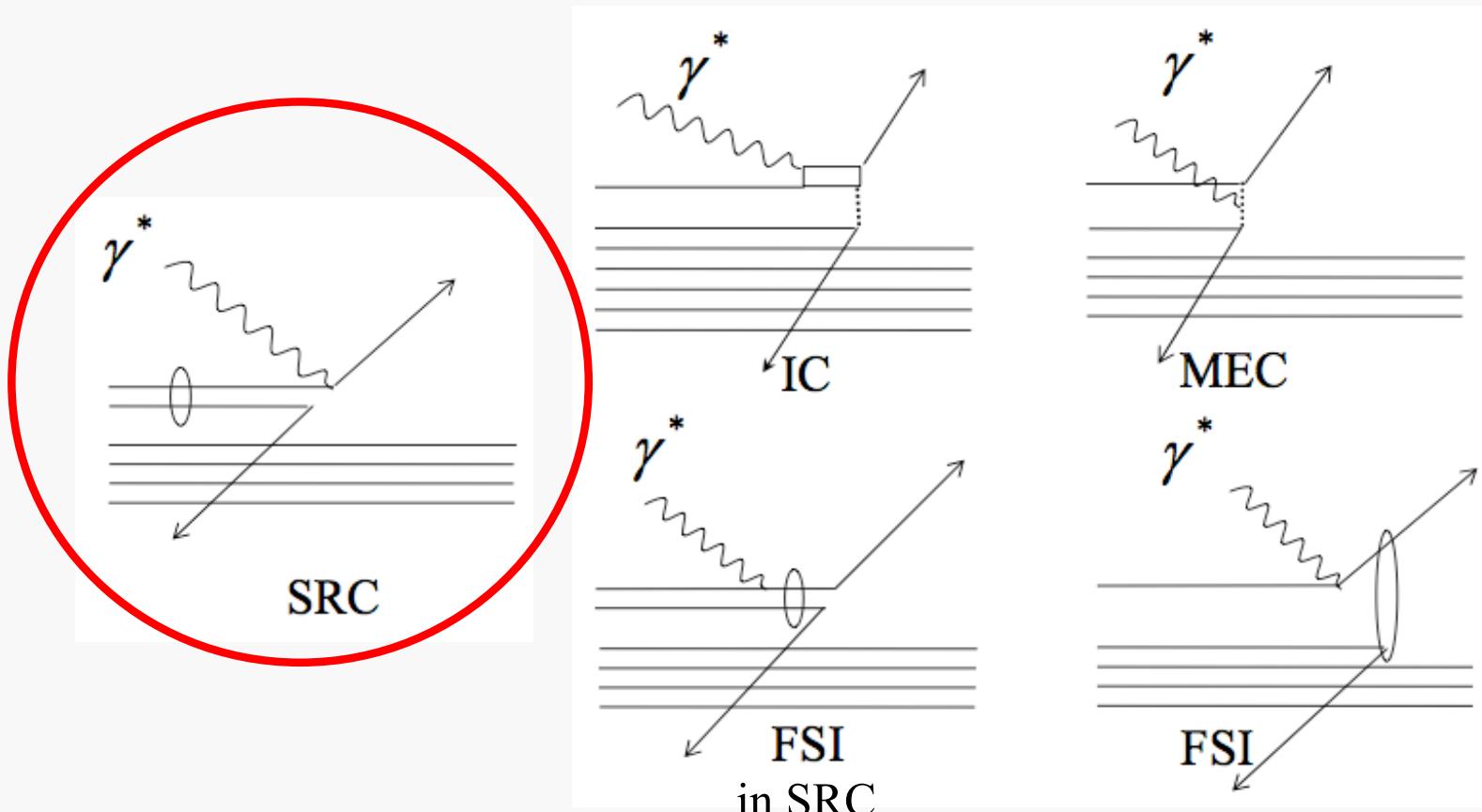


What are correlations?

Average Two-Nucleon Properties in the Nuclear Ground State

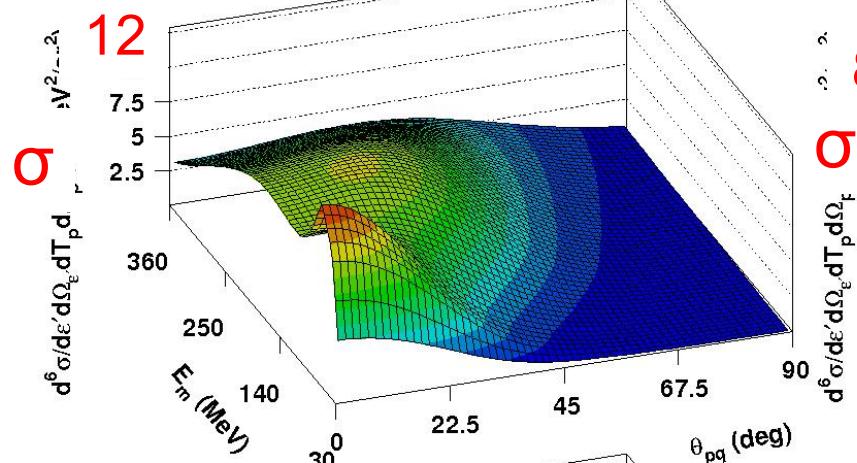
Responsible for the high momentum part of the Nuclear WF

Two-body currents are **not** Correlations
(but everything adds coherently)

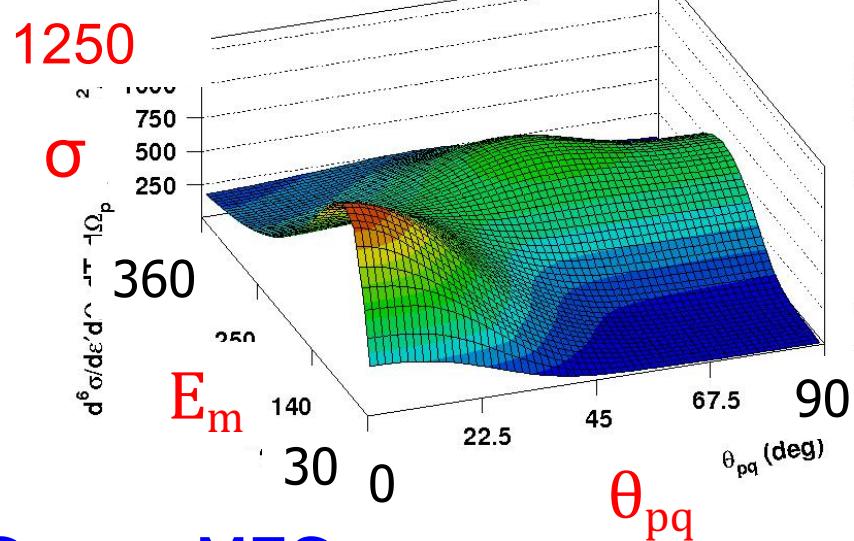
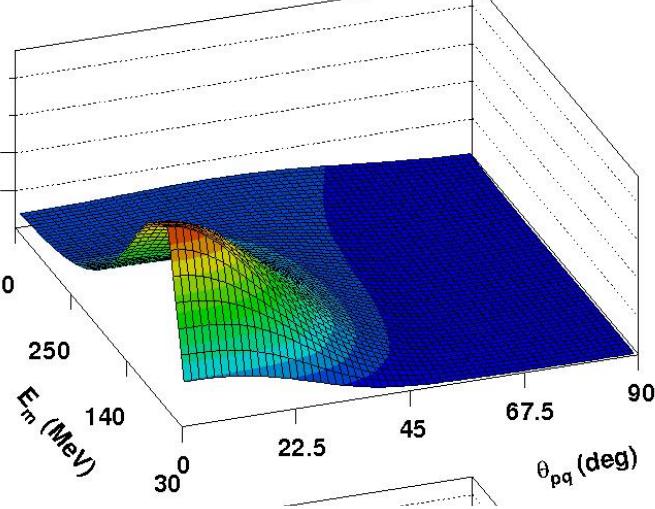


2N currents enhance correlations

Central correlations only



Central + tensor corr



Corr + MEC

MEC and correlations add
coherently
 $\rightarrow 2p2h$

O(e,e'p) Ryckebusch
NP A672 (2000) 285

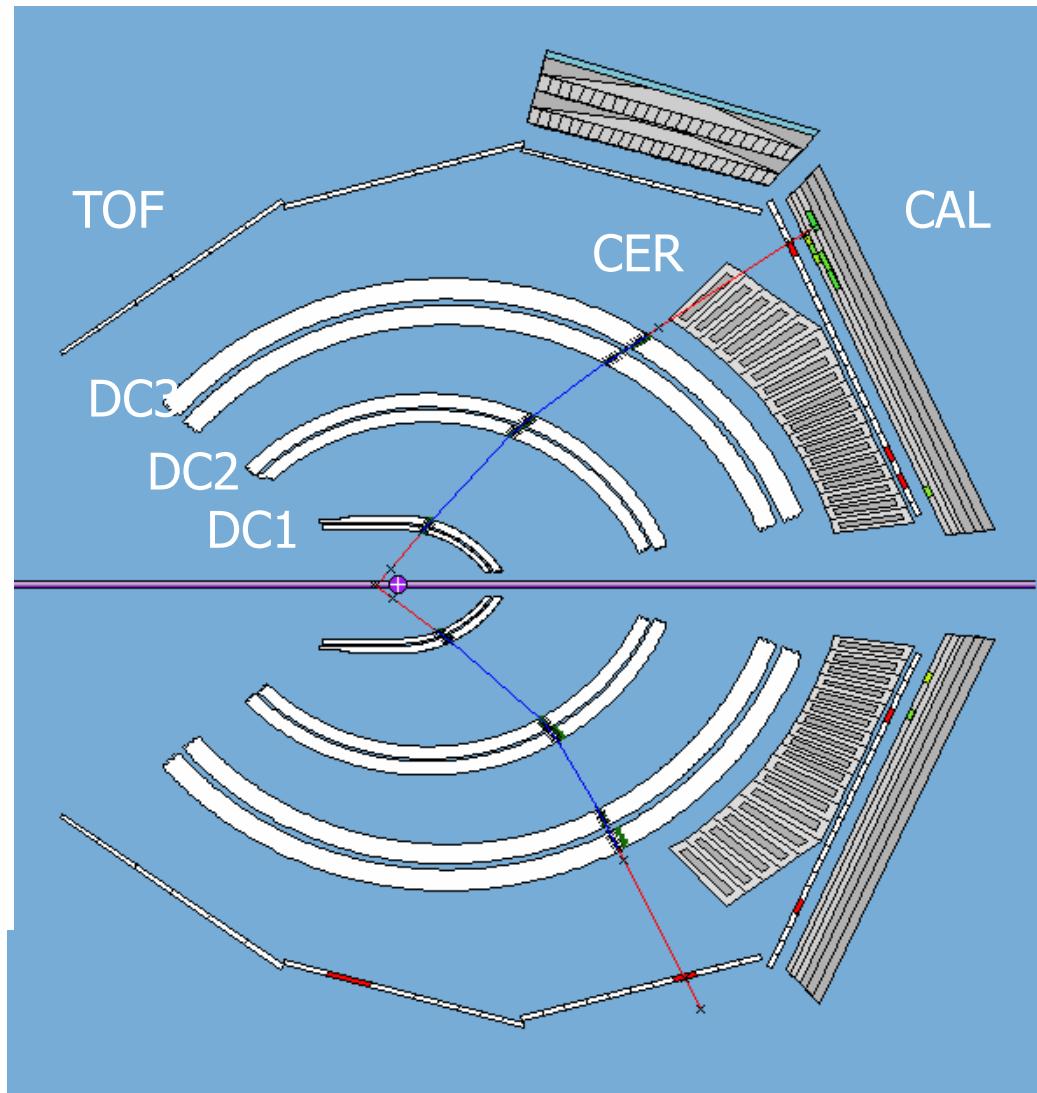
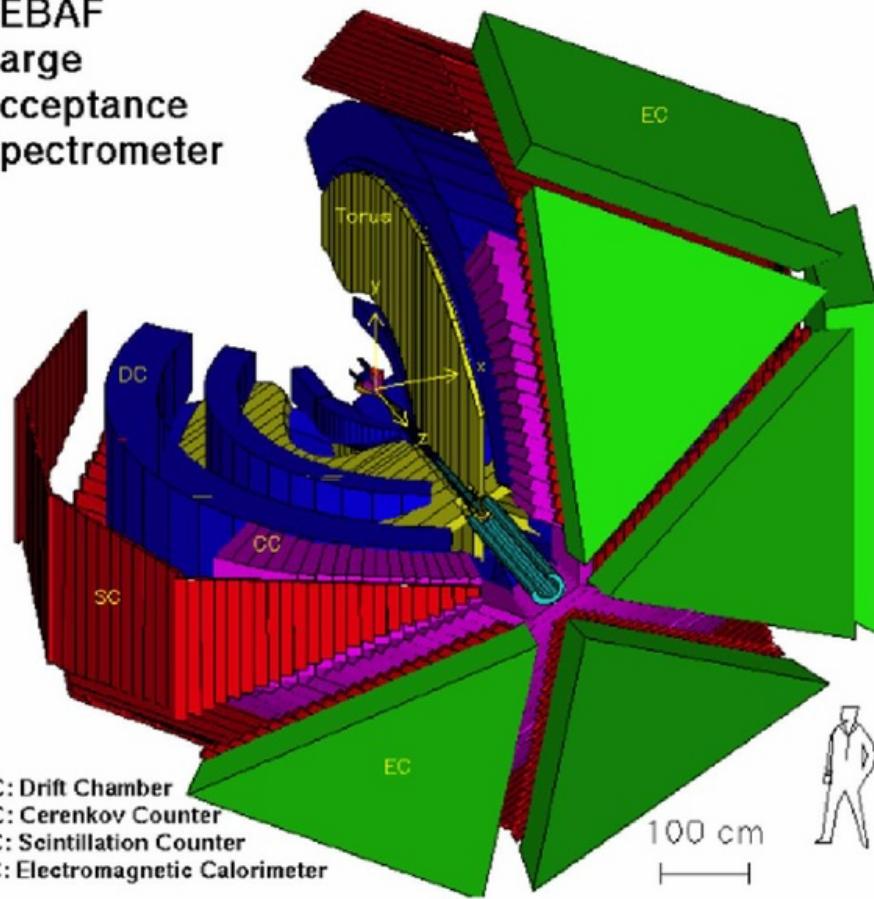
Physics Summary

- Electron scattering:
 - Monochromatic beam
 - Vector current only
 - Can choose kinematics to minimize “uninteresting” reaction mechanisms
 - Calculate cross sections after the fact
- Neutrino interactions
 - Continuous mixed beams
 - Vector plus axial current
 - Must include all reaction mechanisms
 - MEC, IC, correlations, Delta, ...
 - FSI (not discussed here)
 - Need good models in event generators

Jefferson Lab data

CLAS: 1996-2015

CEBAF
Large
Acceptance
Spectrometer



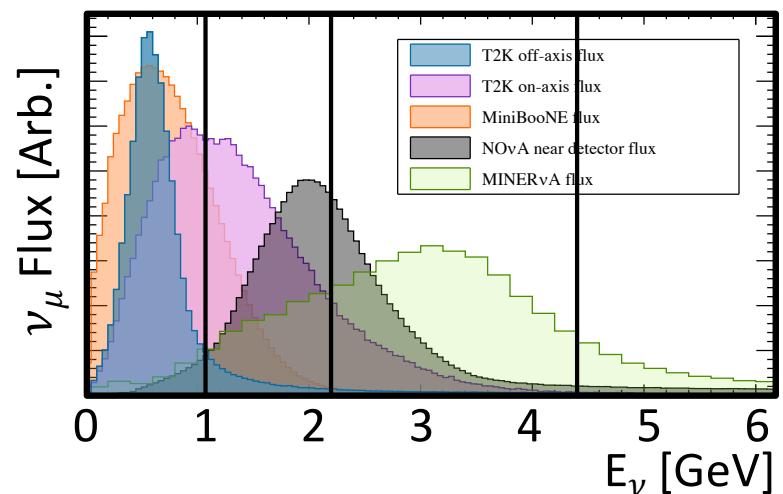
CLAS6 (e,e'p) Data (million events)

	1.1 GeV	2.2 GeV	4.4 GeV
3He	4	9	1
4He	X	17	3
12C	3	11	2
56Fe	X	0.5	0.1

E2a data only.

E2b has more 4.6 GeV 3He and 56Fe

Eg2 has 5 GeV d, C, Al, Fe, and Pb



Reconstructing the initial energy

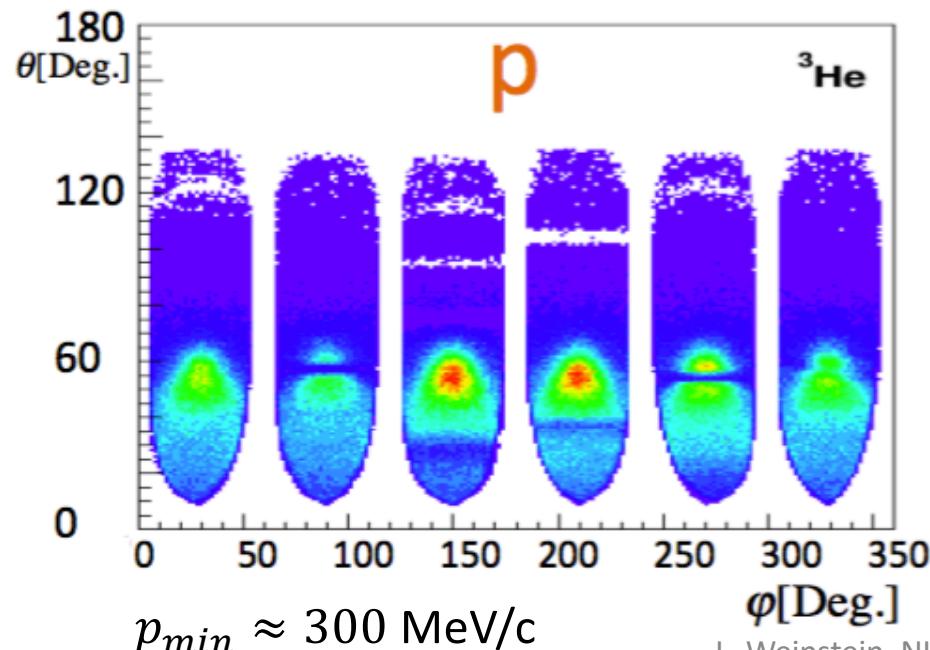
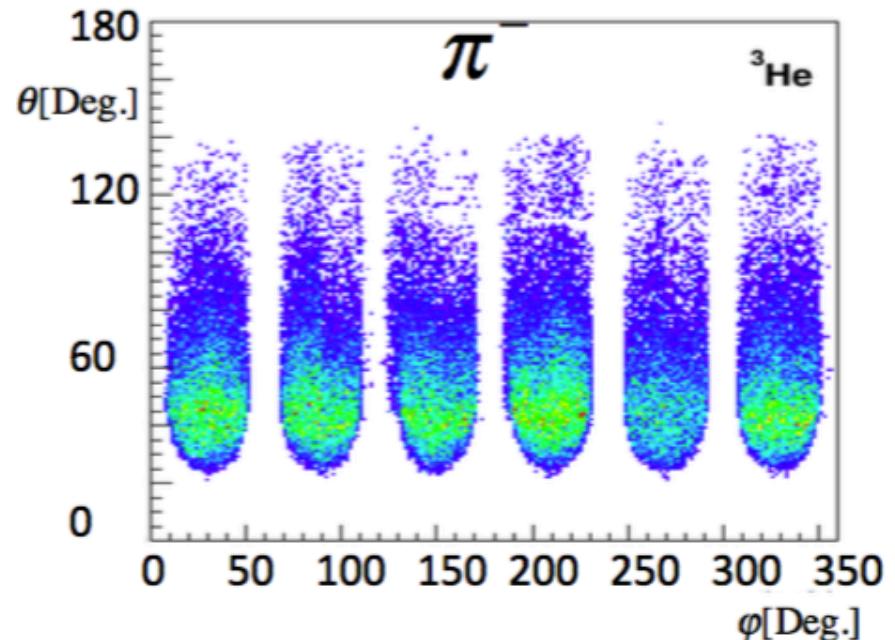
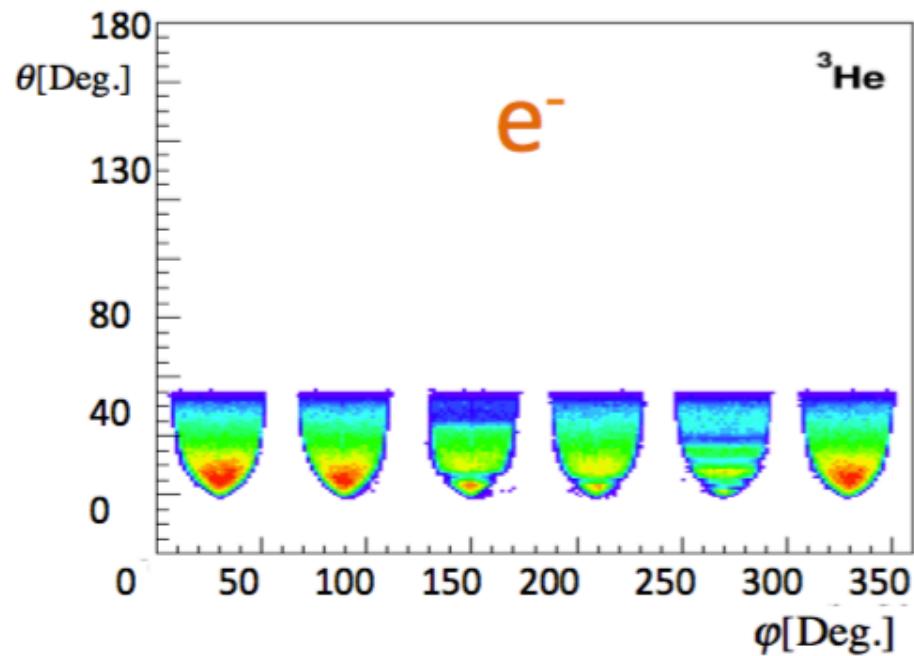
- Choose 0π events to enhance the QE sample
 - Subtract undetected pions and photons
- Weight by $1/\sigma_{Mott}$ to account for photon propagator
- Reconstruct the incident lepton energy:

$$- E_{QE} = \frac{2M_N\epsilon + 2M_NE_l - m_l^2}{2(M_N - E_l + k_l \cos\theta_l)}$$

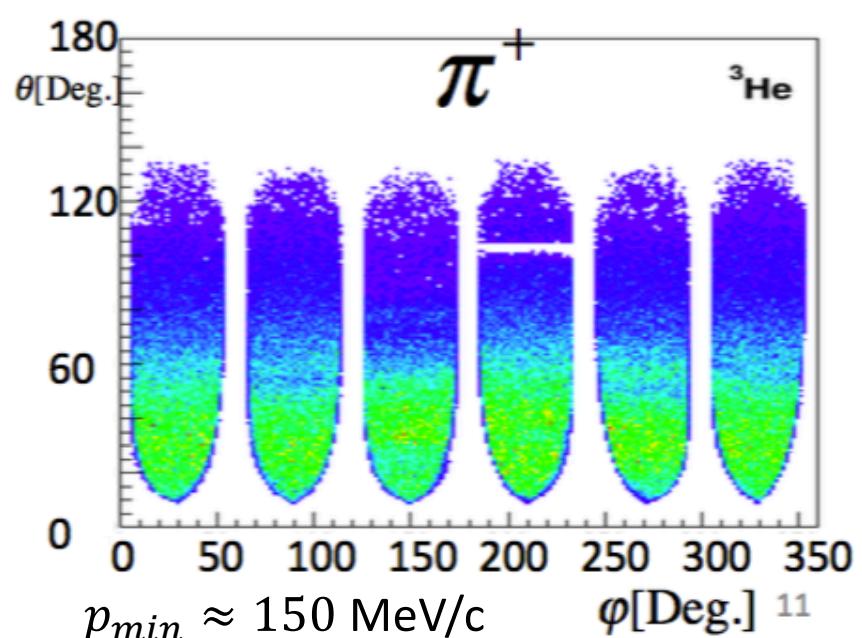
- ϵ : nucleon separation energy, M_N nucleon mass
- $\{m_l, E_l, k_l, \theta_l\}$ scattered lepton mass, energy, momentum and angle
- broadened by nucleon fermi motion

$$- E_{cal} = E_e + T_p + \epsilon \quad [\text{for (e,e'p) }]$$

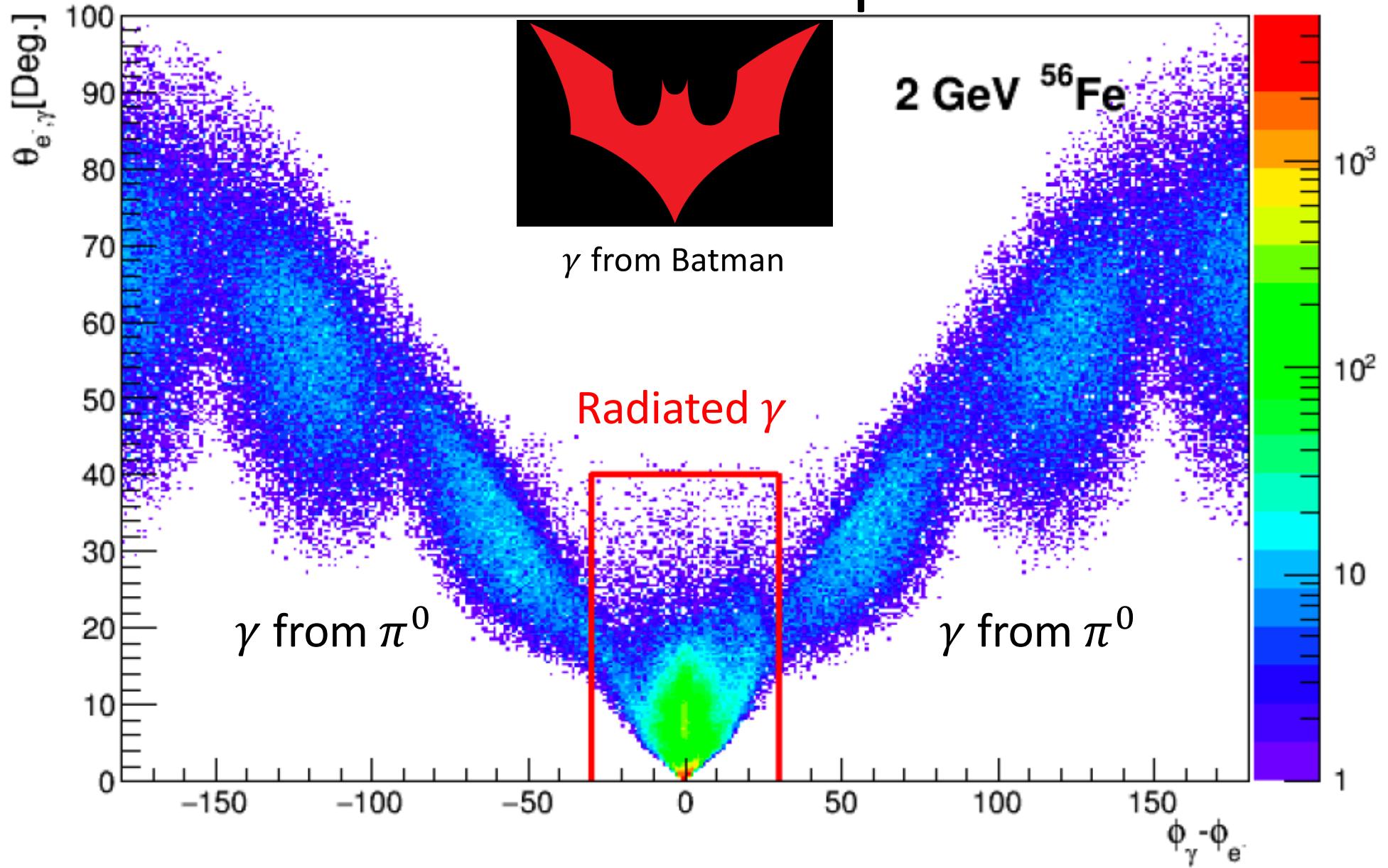
CLAS6 coverage



L. Weinstein, NUSTEC 2019



Exclude radiated photons



Background Subtraction

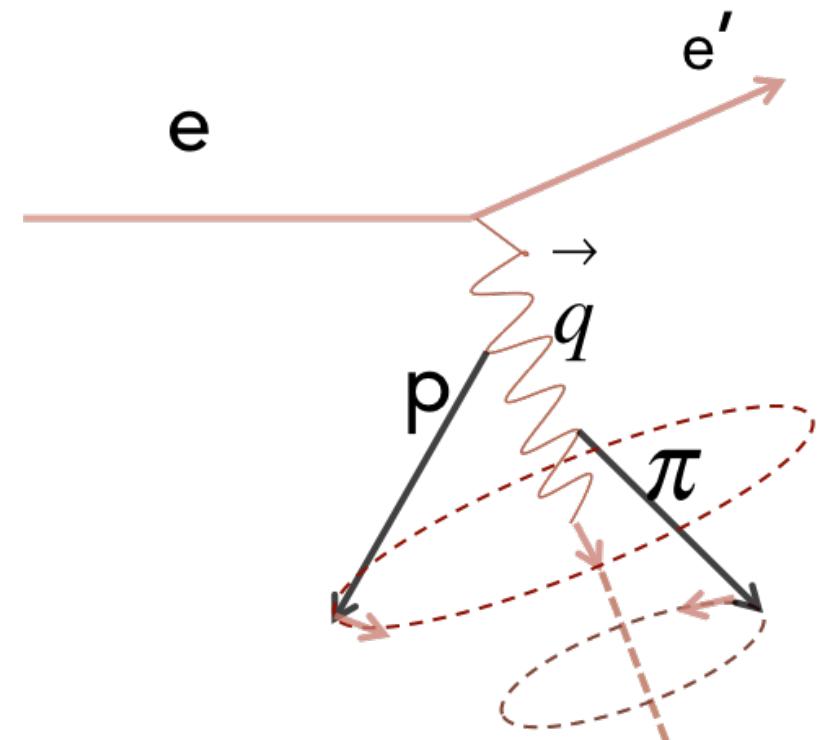
Want 0π event sample

(e,e') background: undetected pions and photons

(e,e'p) background: undetected pions, photons and extra protons

Data Driven Correction:

1. Use measured (e,e'p π/γ) events,
2. Rotate π or γ around \mathbf{q} to determine its acceptance,
3. Subtract (e,e'p π/γ) contributions



Background Subtraction

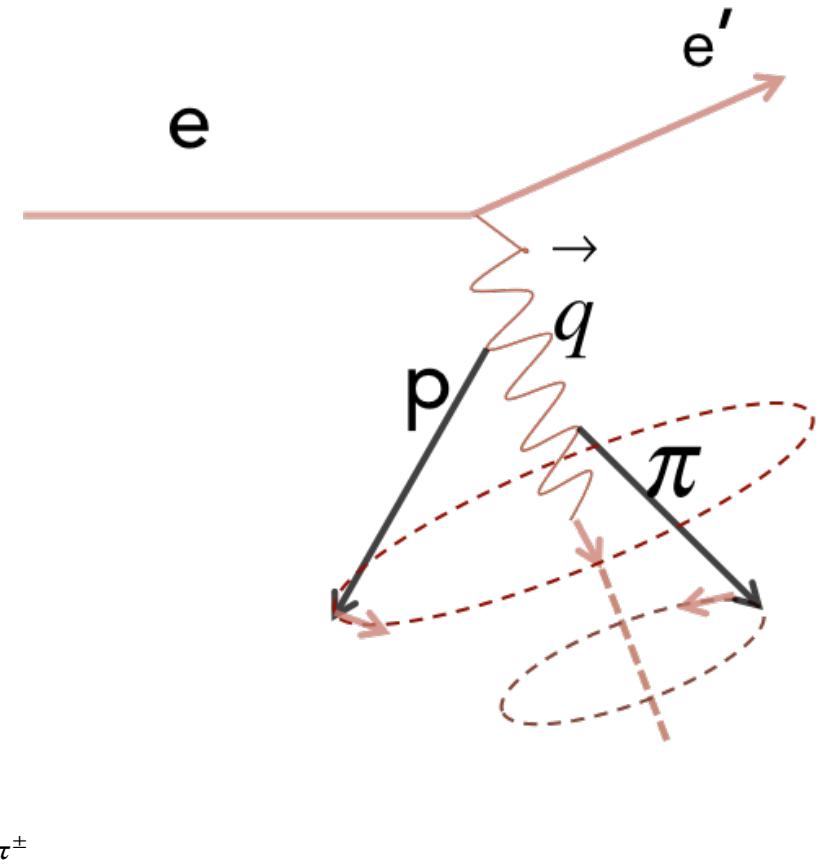
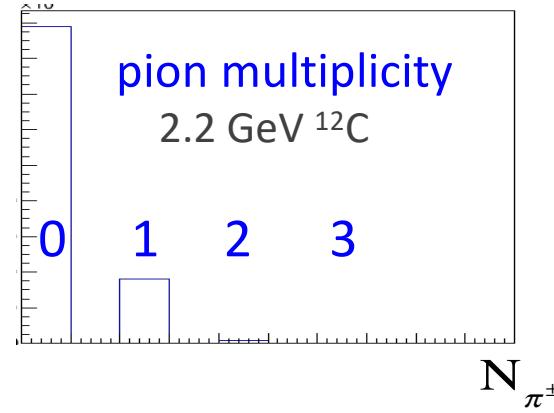
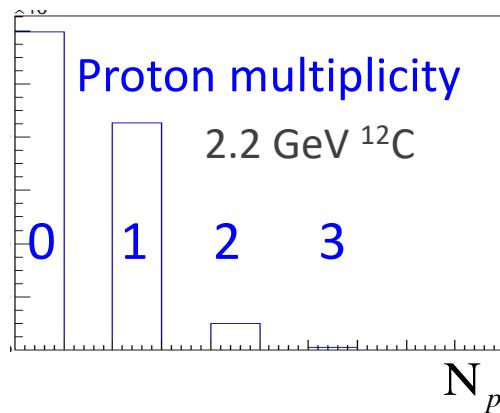
Want 0π event sample

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3. Subtract (e,e'p π/γ) contributions
4. Do the same for 2p, 3p, 2p+ π etc.



Background Subtraction

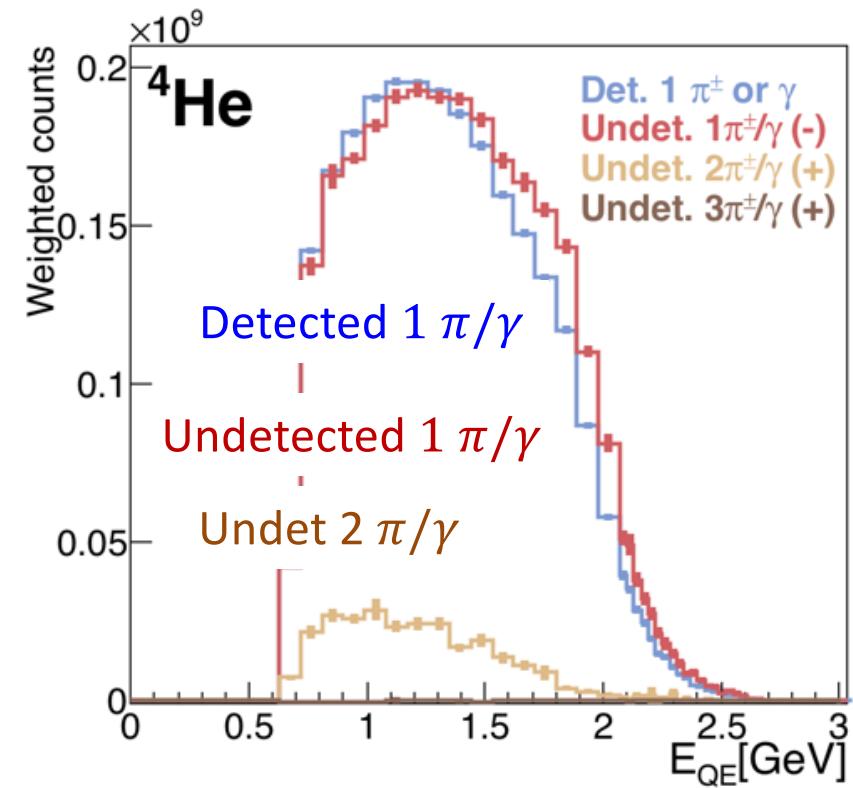
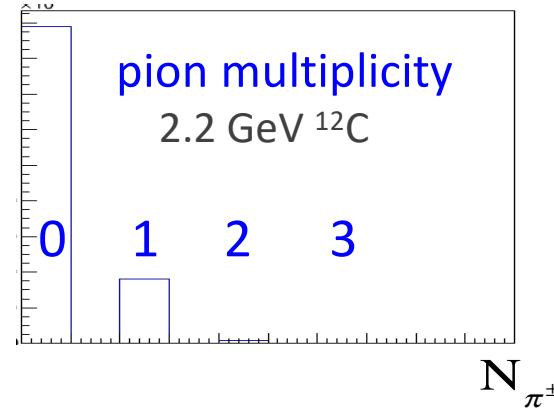
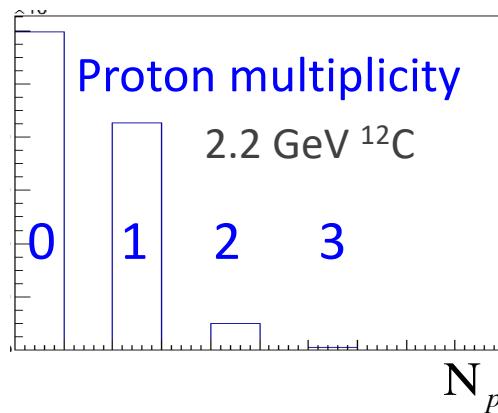
Want 0π event sample

(e,e') background: undetected pions and photons

(e,e'p) background: undetected pions, photons and extra protons

Data Driven Correction:

1. Use measured (e,e'p π/γ) events
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Background Subtraction

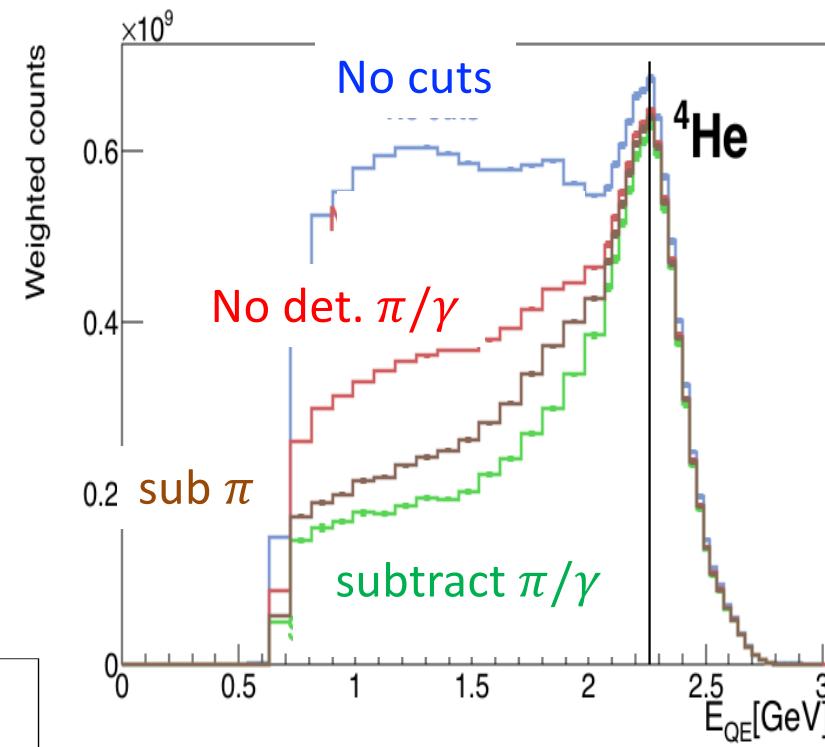
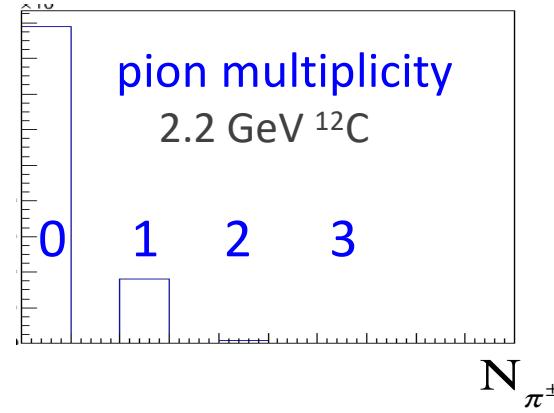
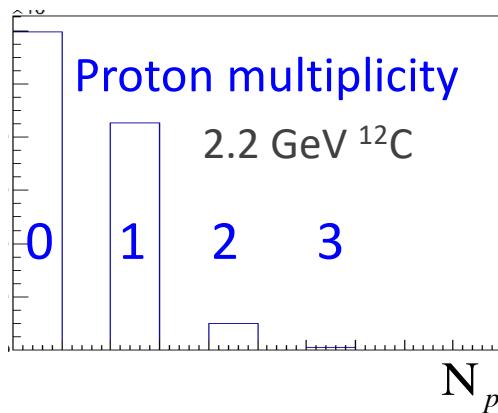
Want 0π event sample

(e,e') background: undetected pions and photons

(e,e'p) background: undetected pions, photons and extra protons

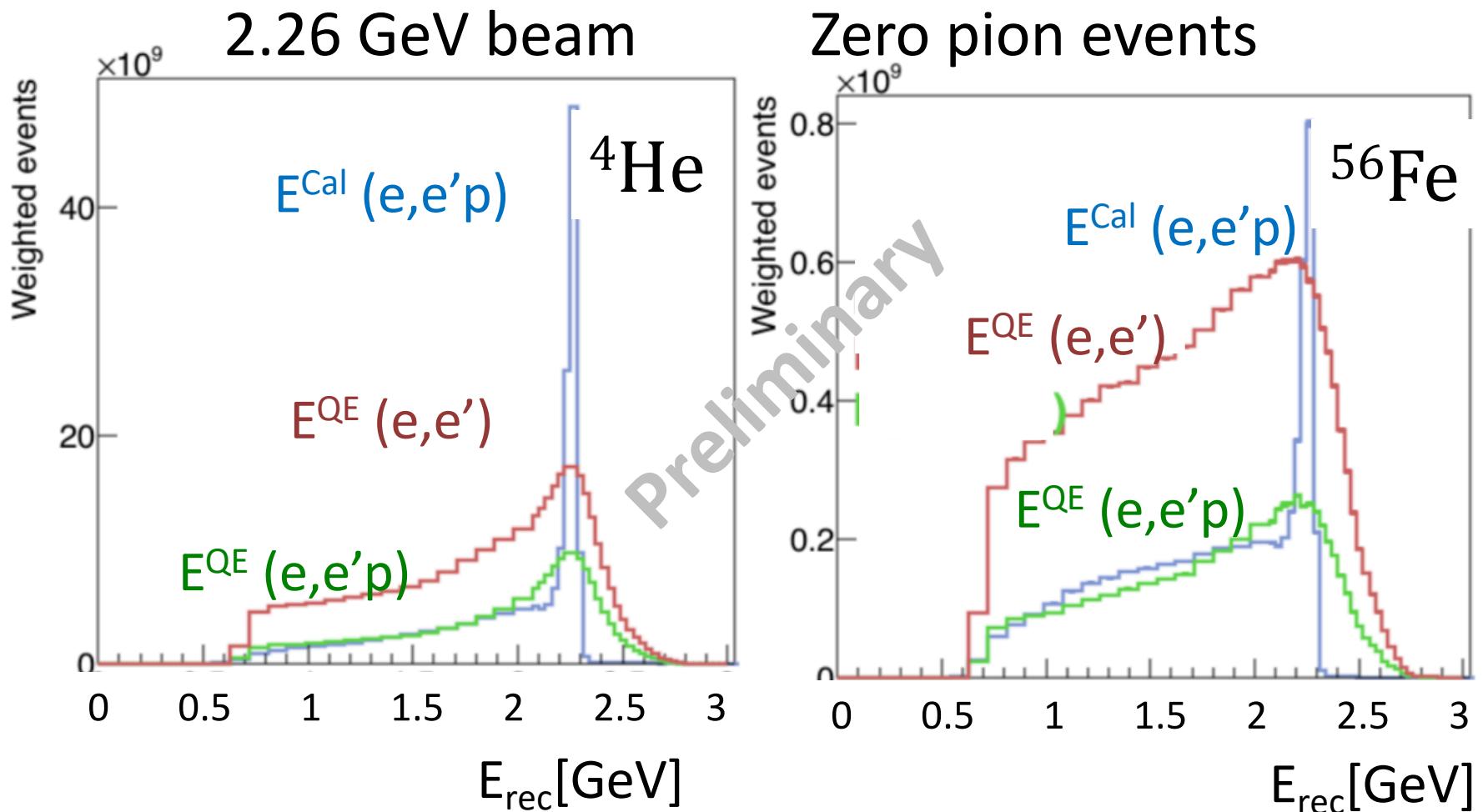
Data Driven Correction:

1. Use measured (e,e'p π/γ) events
2. Rotate π or γ around \mathbf{q} to determine its acceptance,
3. Subtract (e,e'p π/γ) contributions
4. Do the same for 2p, 3p, 2p+ π etc.



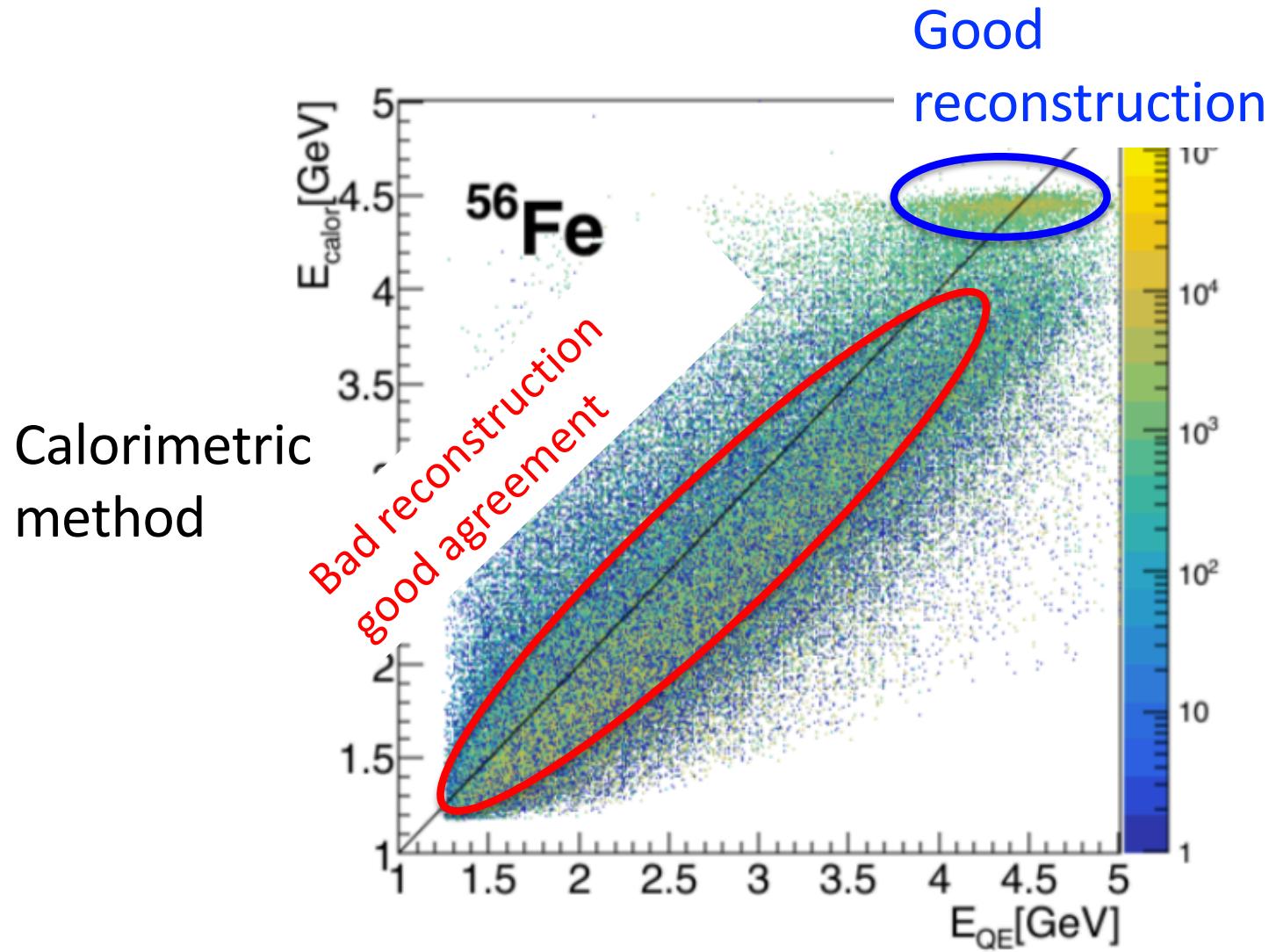
→ True 0π event sample!

Energy Reconstruction: A dependence

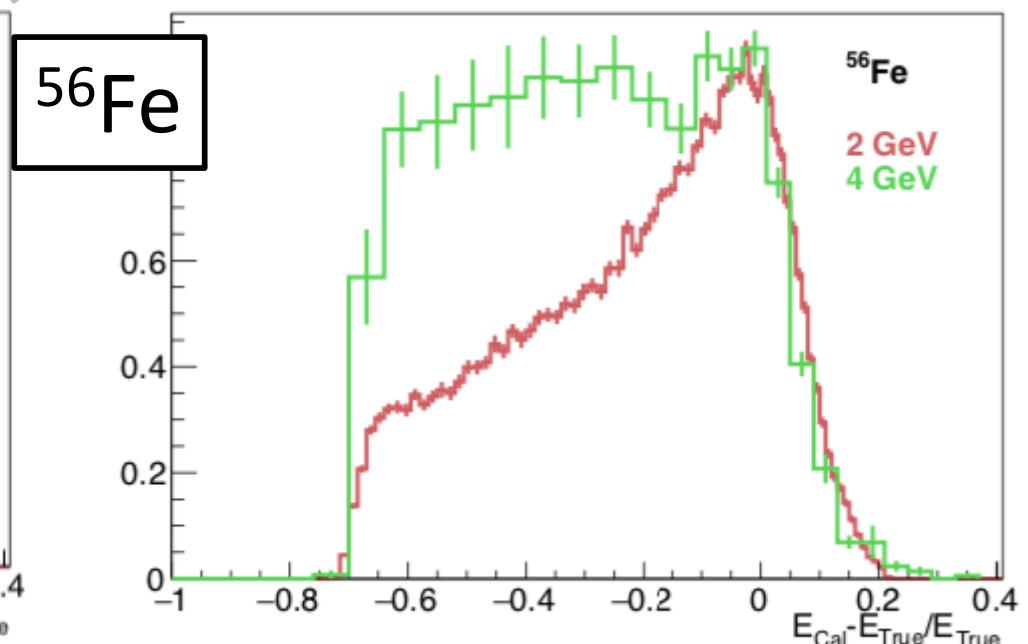
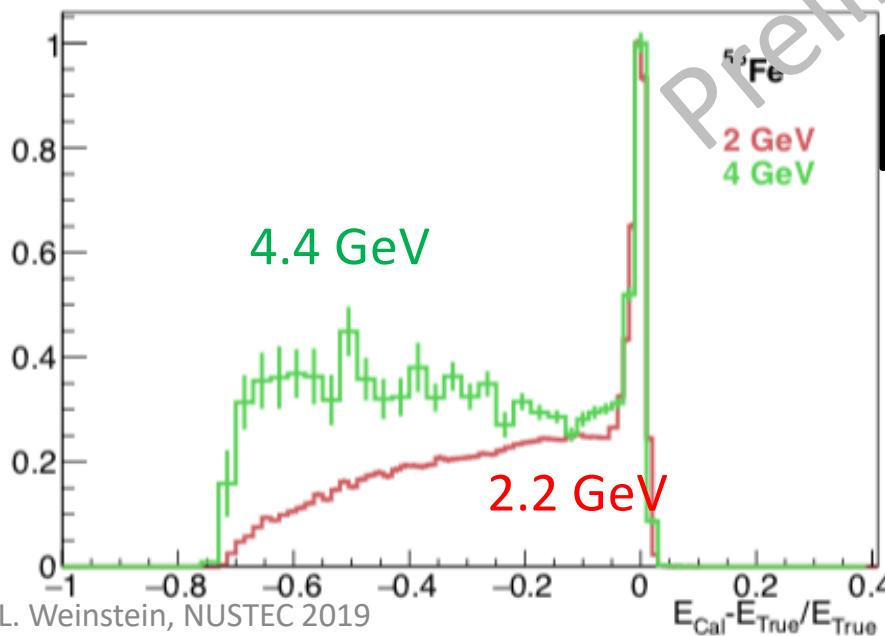
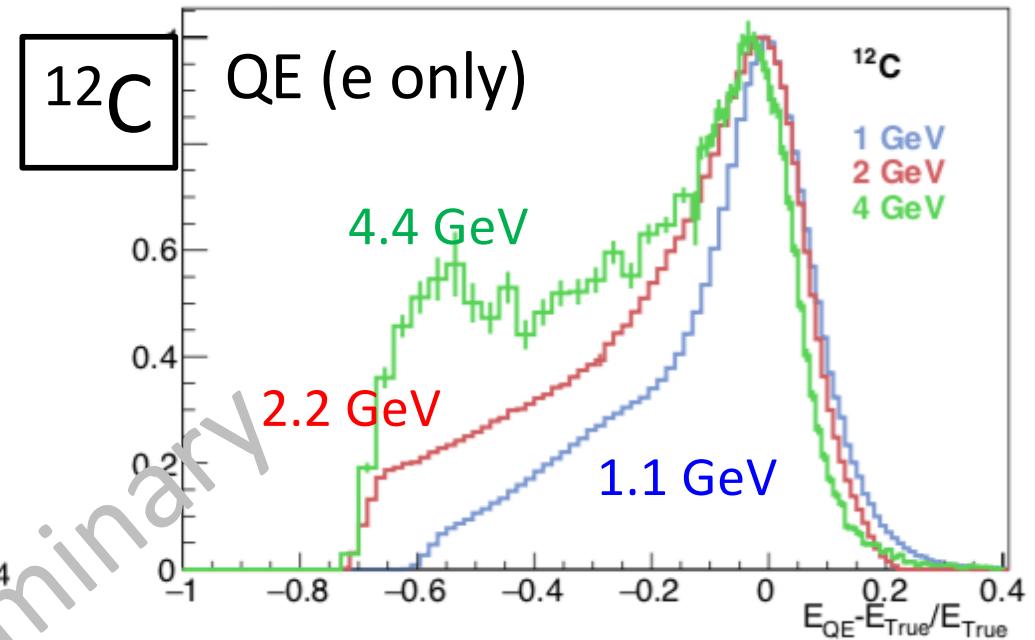
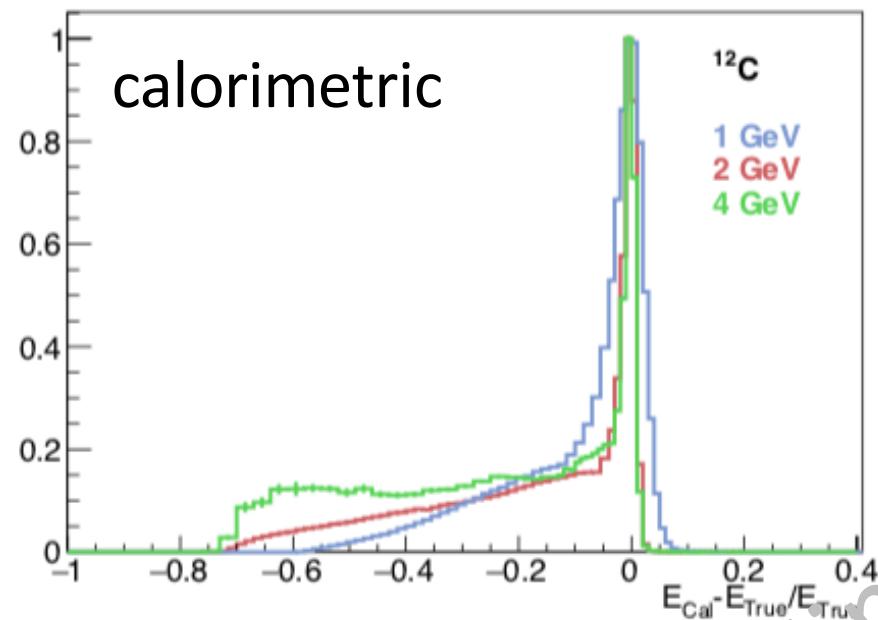


- Even 0pi events have a LOT of non-QE events
 - Much bigger in Fe than ${}^4\text{He}$
 - Same long tail for E_{cal} and E_{QE}

Agreement between methods does not guarantee correctness

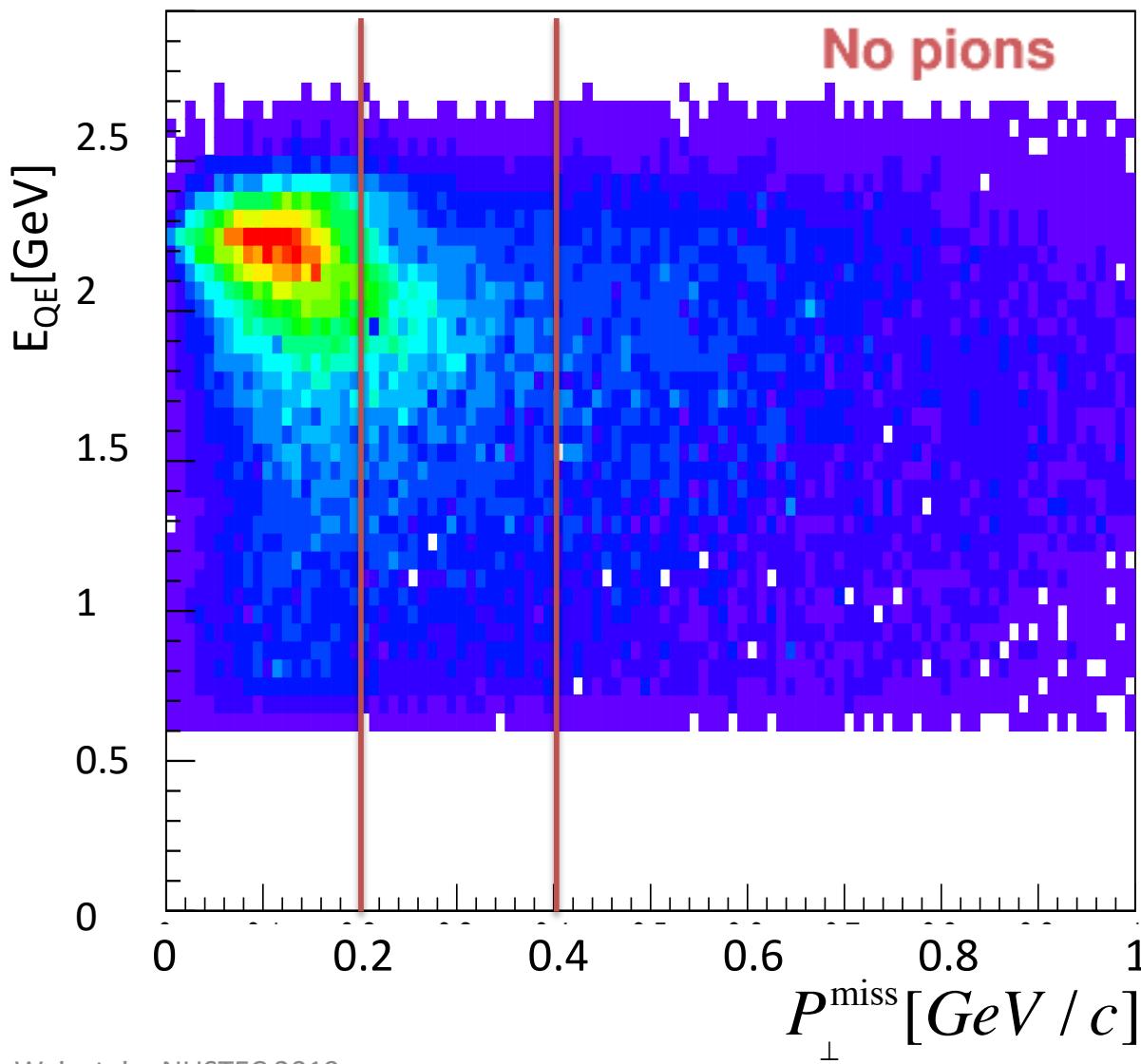


Fractional Energy Feeddown

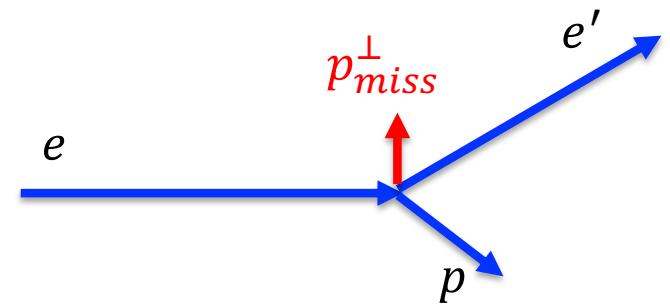


Can we select QE events?

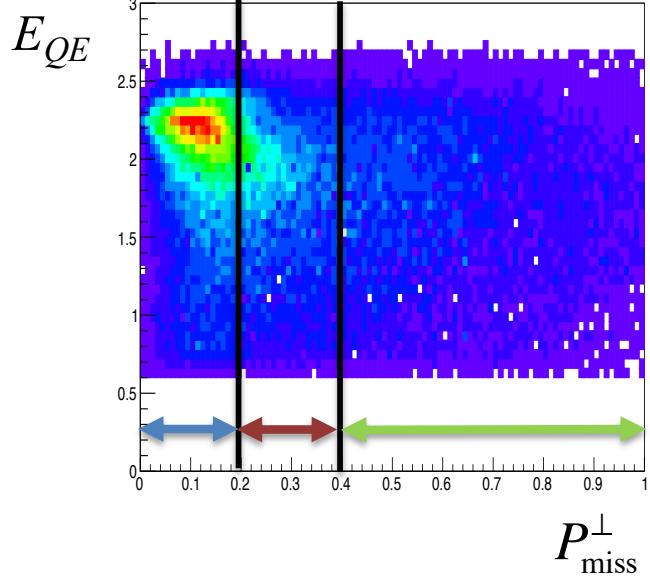
2.2 GeV ^{56}Fe



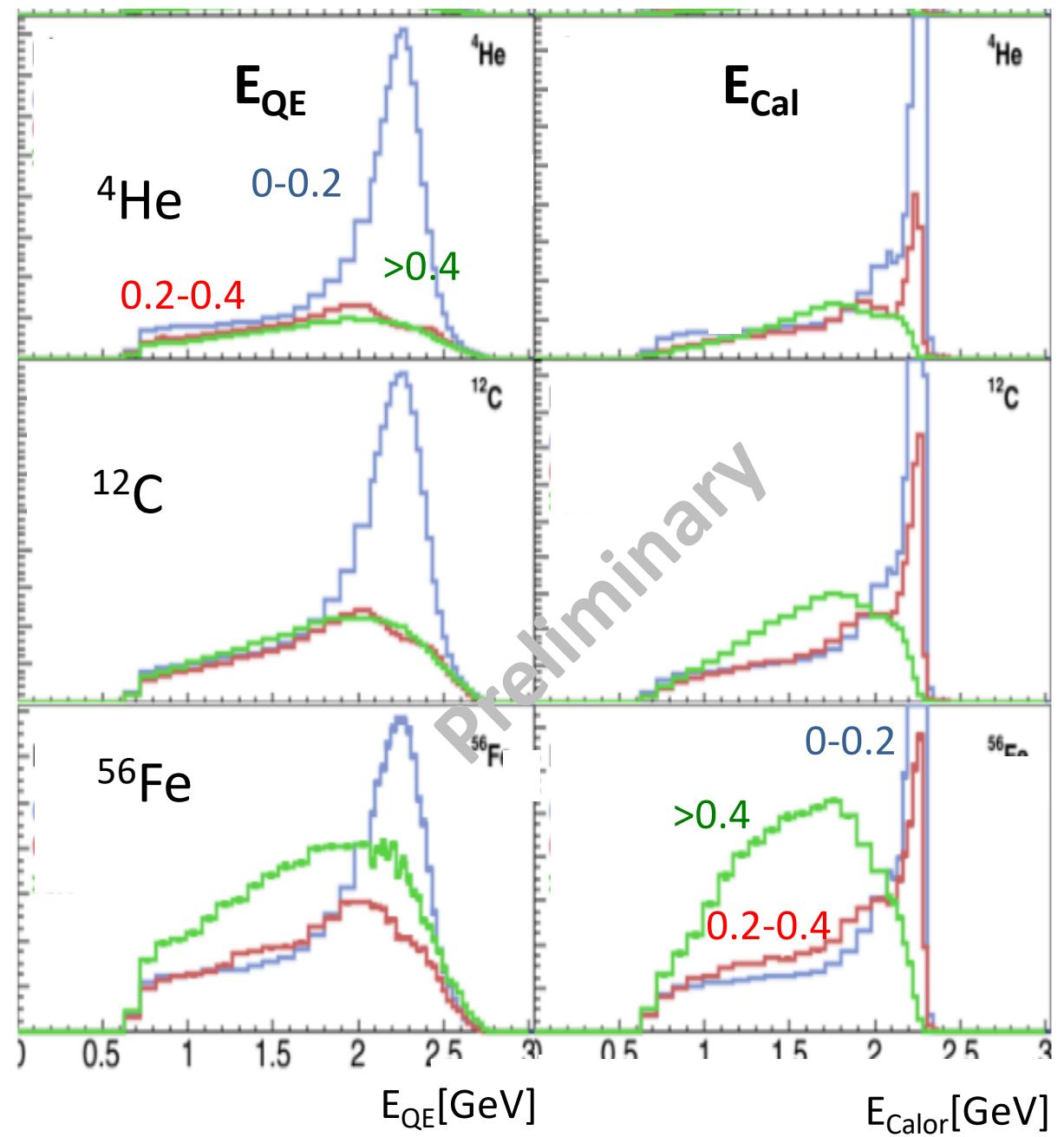
$$P_{\text{miss}}^{\perp} = P_{e^-}^{\perp} + P_p^{\perp} \approx P_{\text{init}}^{\perp}$$



P_{miss}^{\perp} slices

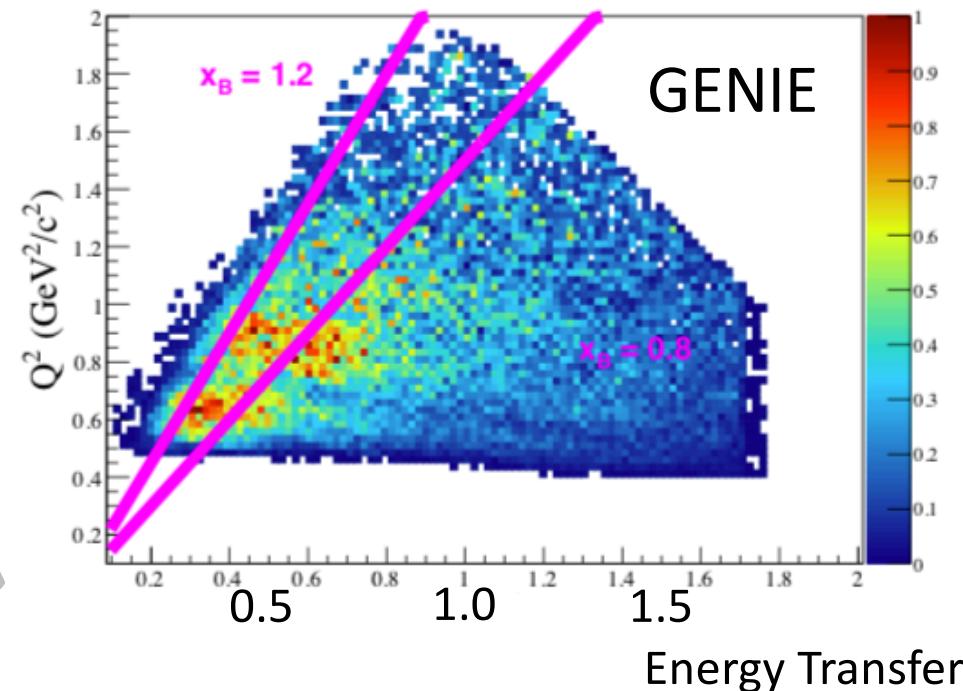
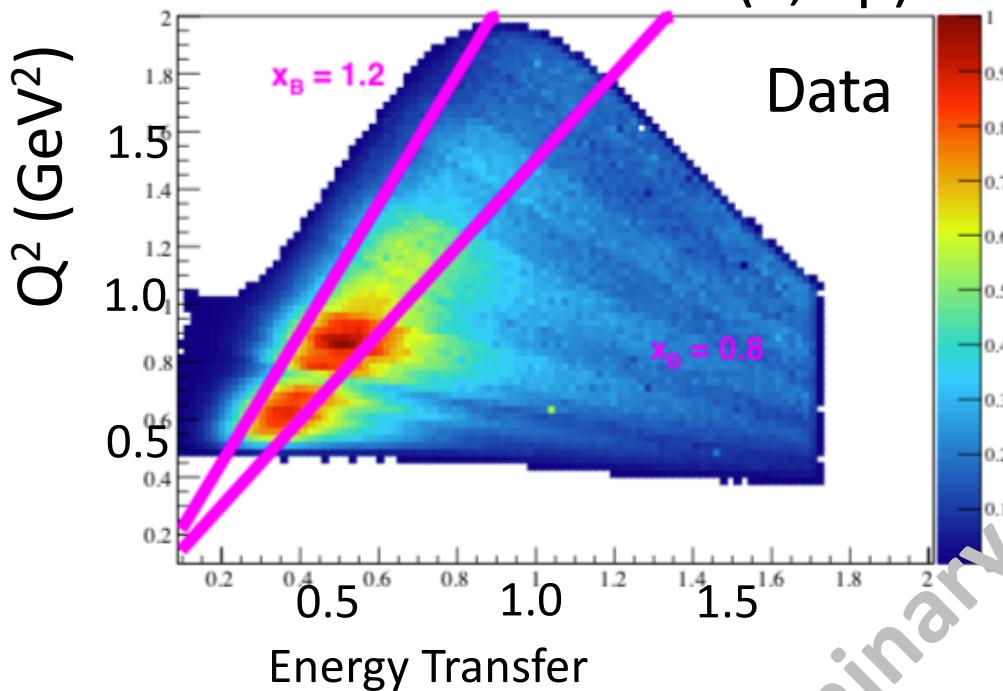


High p_{miss}^{\perp}
 \rightarrow wrong energy!



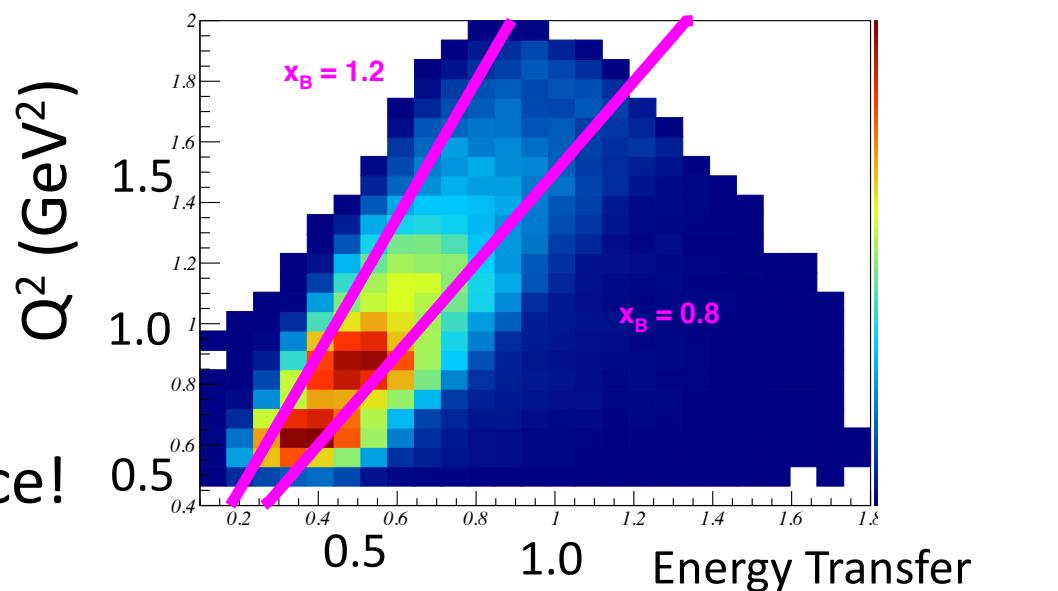
0π Data vs Genie 2.2 GeV

$C(e,e'p)$ 2.26 GeV



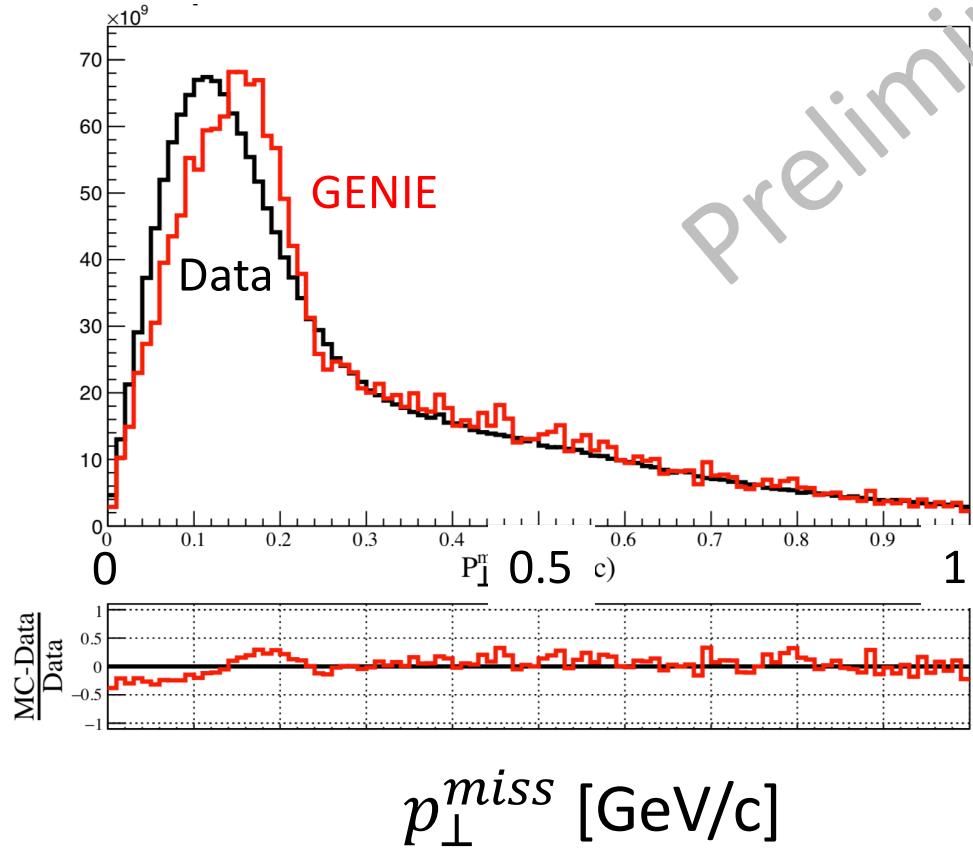
0π does not mean QE!

GENIE
No resonance!

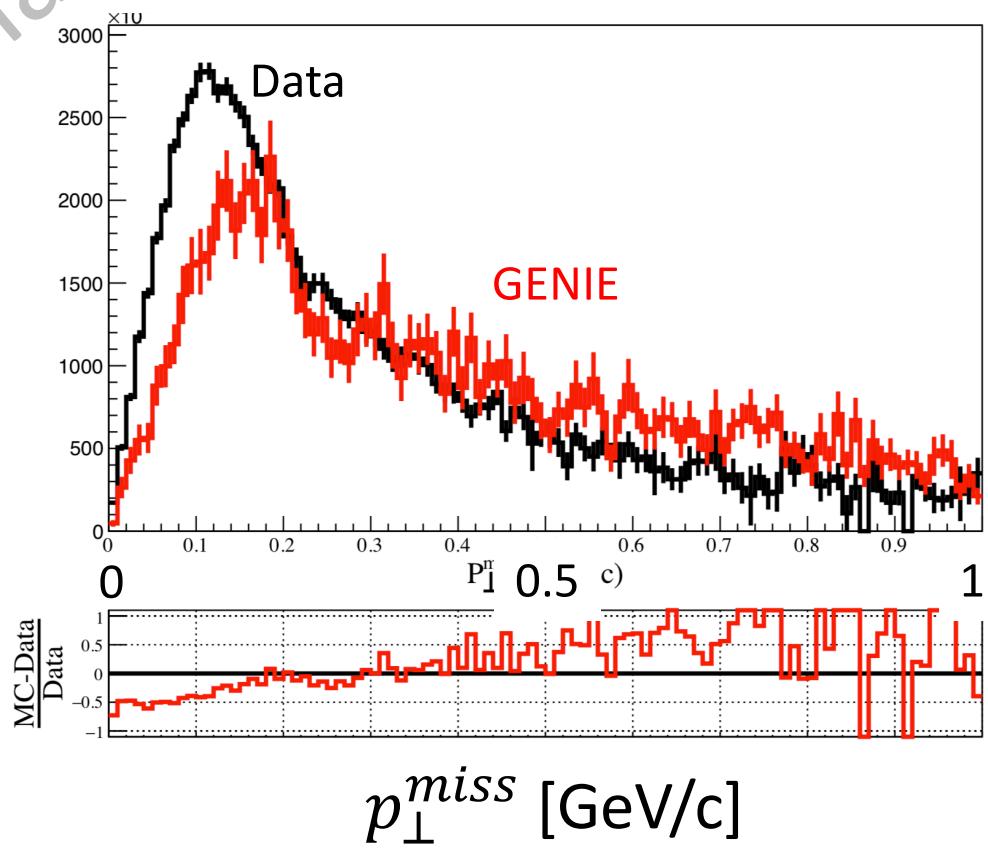


0π Data vs GENIE

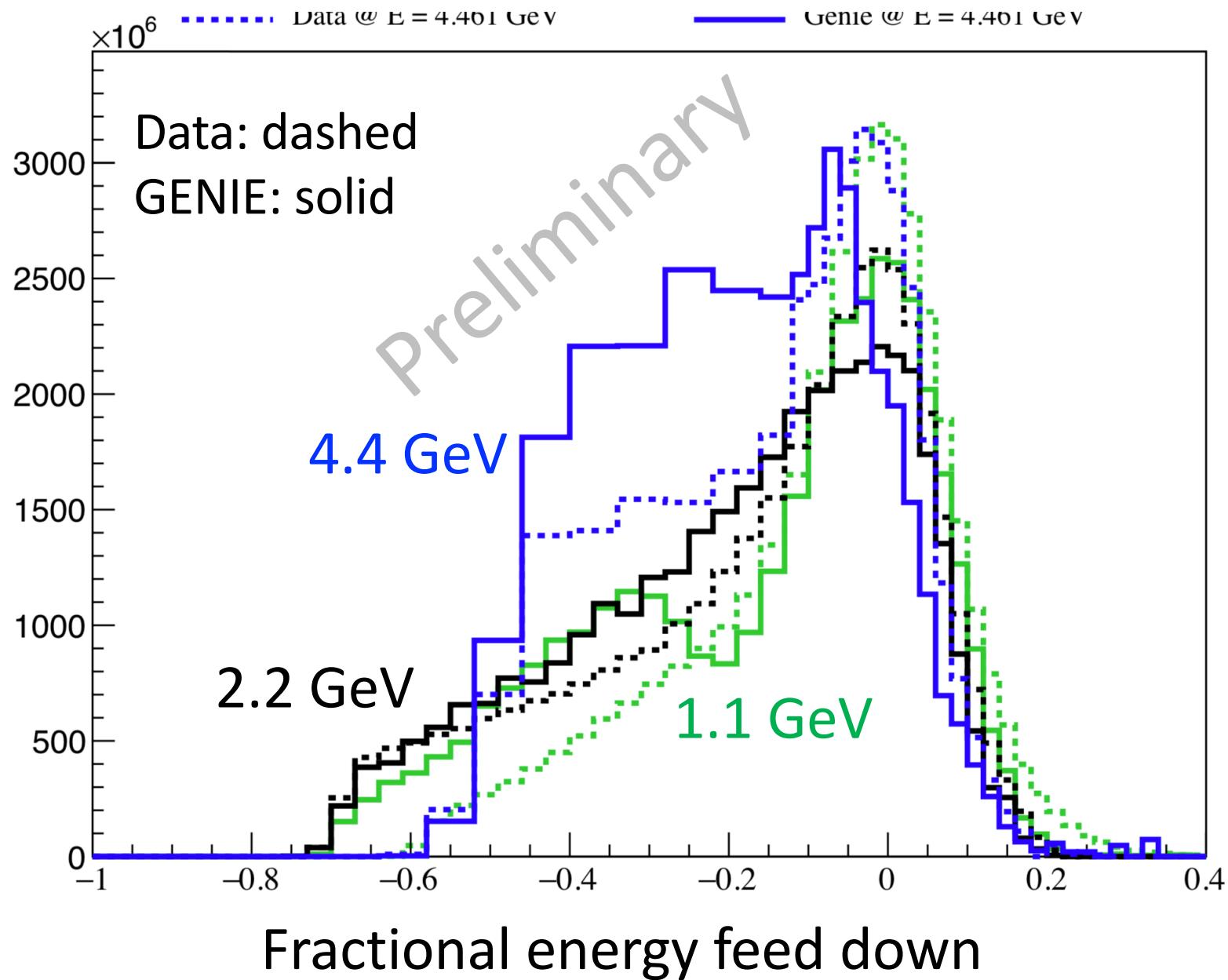
C 2.2 GeV



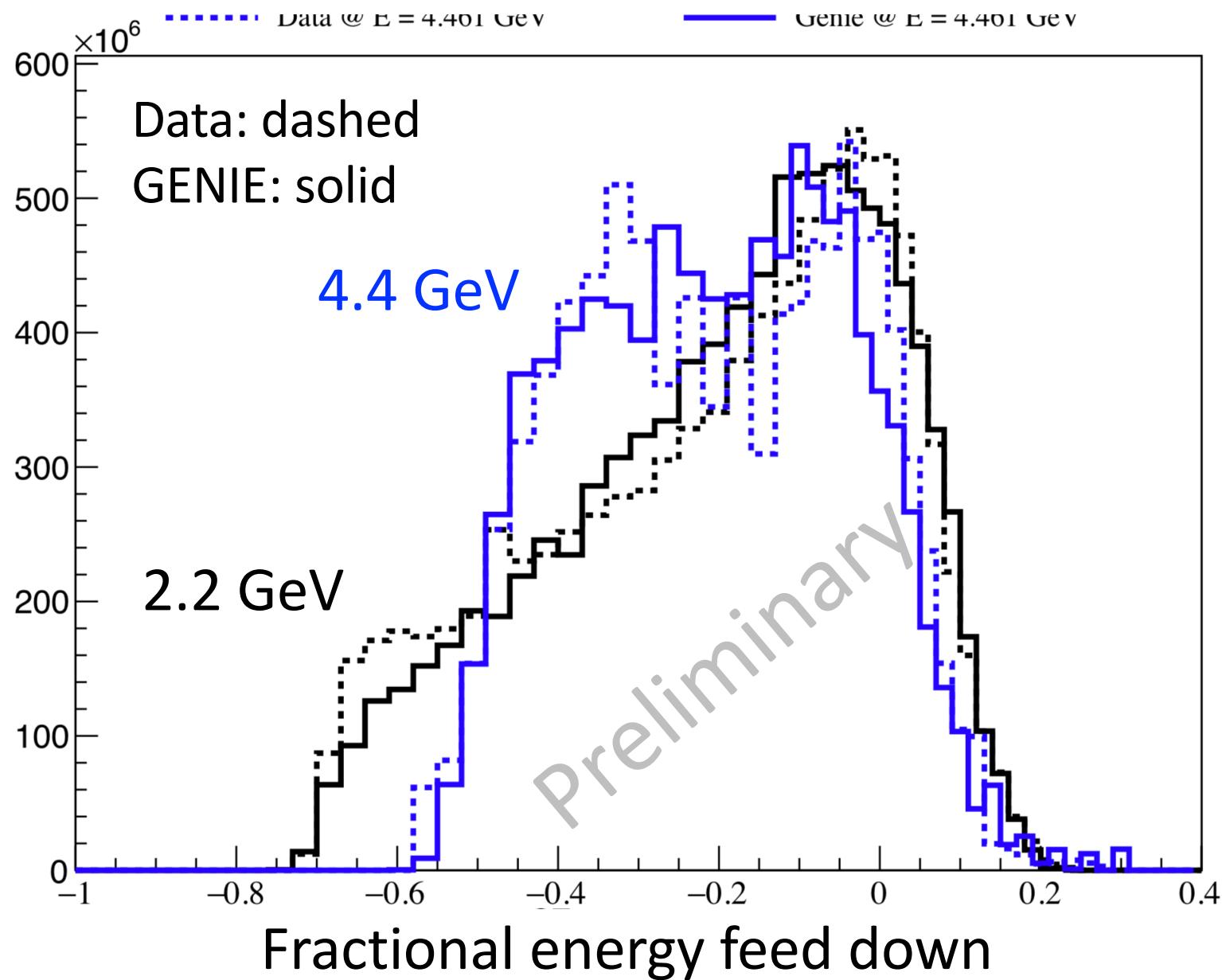
C 4.4 GeV



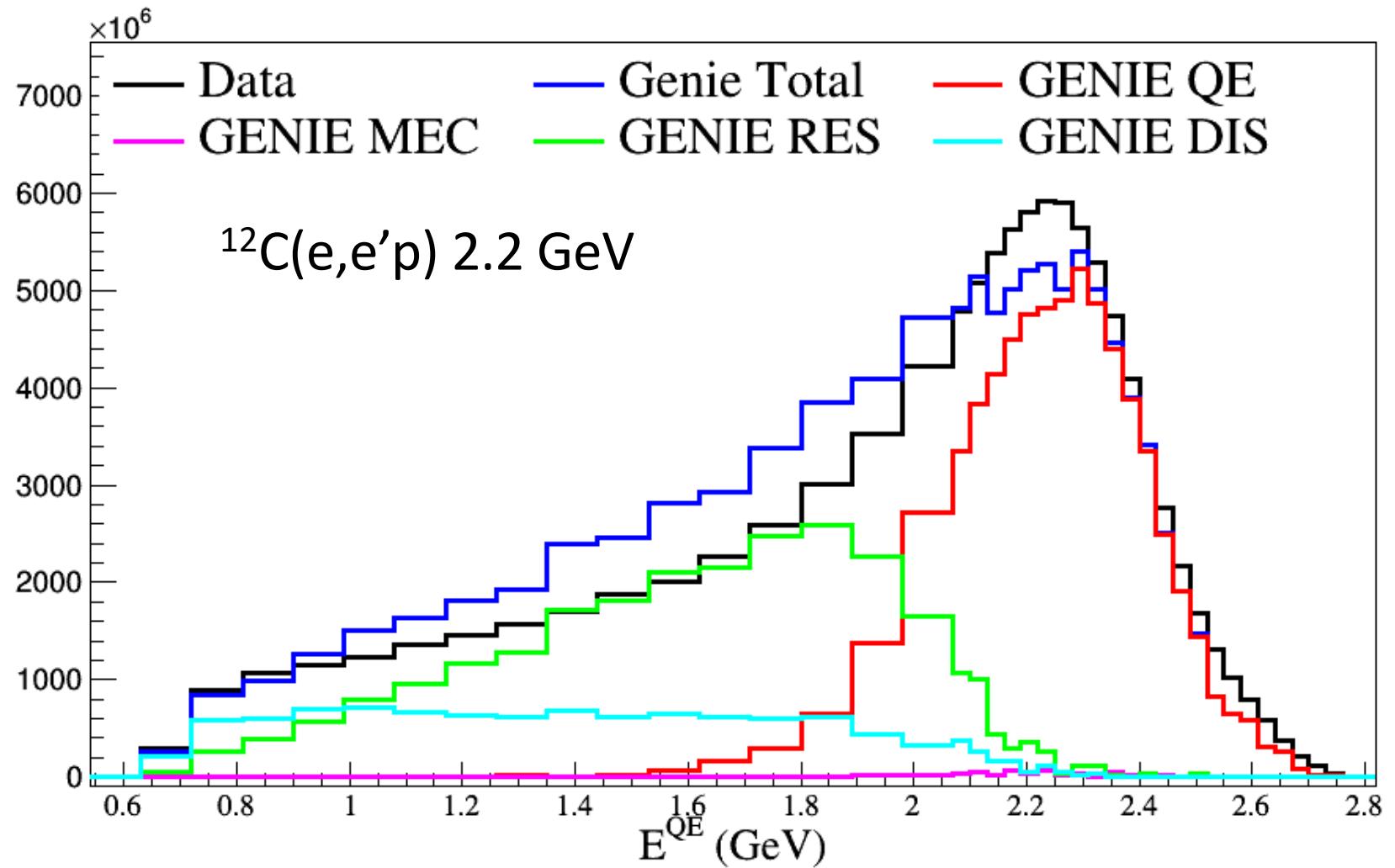
0π Data vs GENIE: Carbon



0π Data vs GENIE: Iron



0π GENIE energy recon



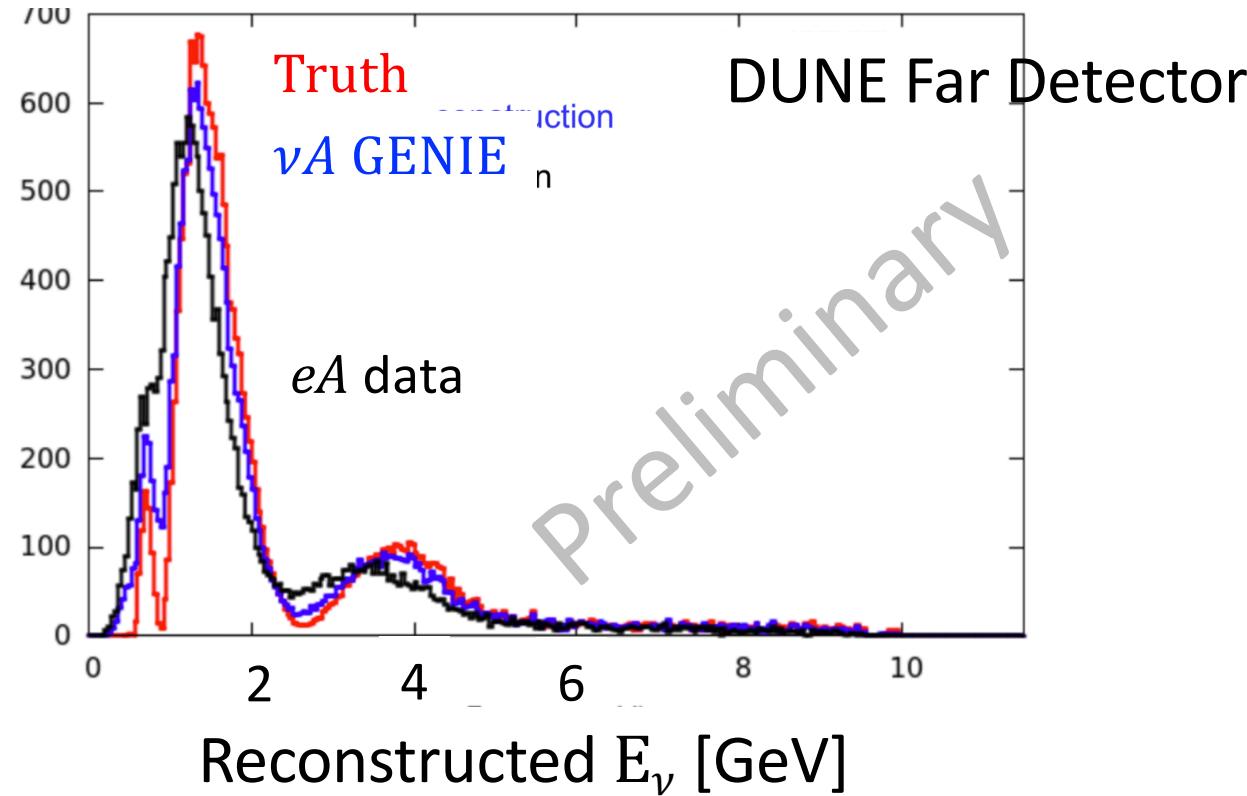
The tail is entirely RES + DIS

Data vs Genie: E_{beam} Reconstruction

Fe	e ⁻ Data	e GENIE
2.2 GeV	26%	29%
4.4 GeV	16%	21%

Fraction of Fe($e, e' p$) events with E_{Cal} within 5% of E_{beam}

Apply QE CLAS data to DUNE Oscillation



- Threw events with νA Genie
 - Reconstructed with νA GENIE or $e A$ data
- Compared E_{rec} for $e A$ to E_{rec} for νA

New analysis: one pion channel ($e, e' p \pi$)

Three energy reconstruction methods:

1. Kinematic (e only), assumes intermediate Δ

$$\bullet \quad E = \frac{m_\Delta^2 - m'^2 - 2m'E'_e}{2(m' - E'_e + E'_e \cos\theta_e)} \quad m' = m_p - \epsilon$$

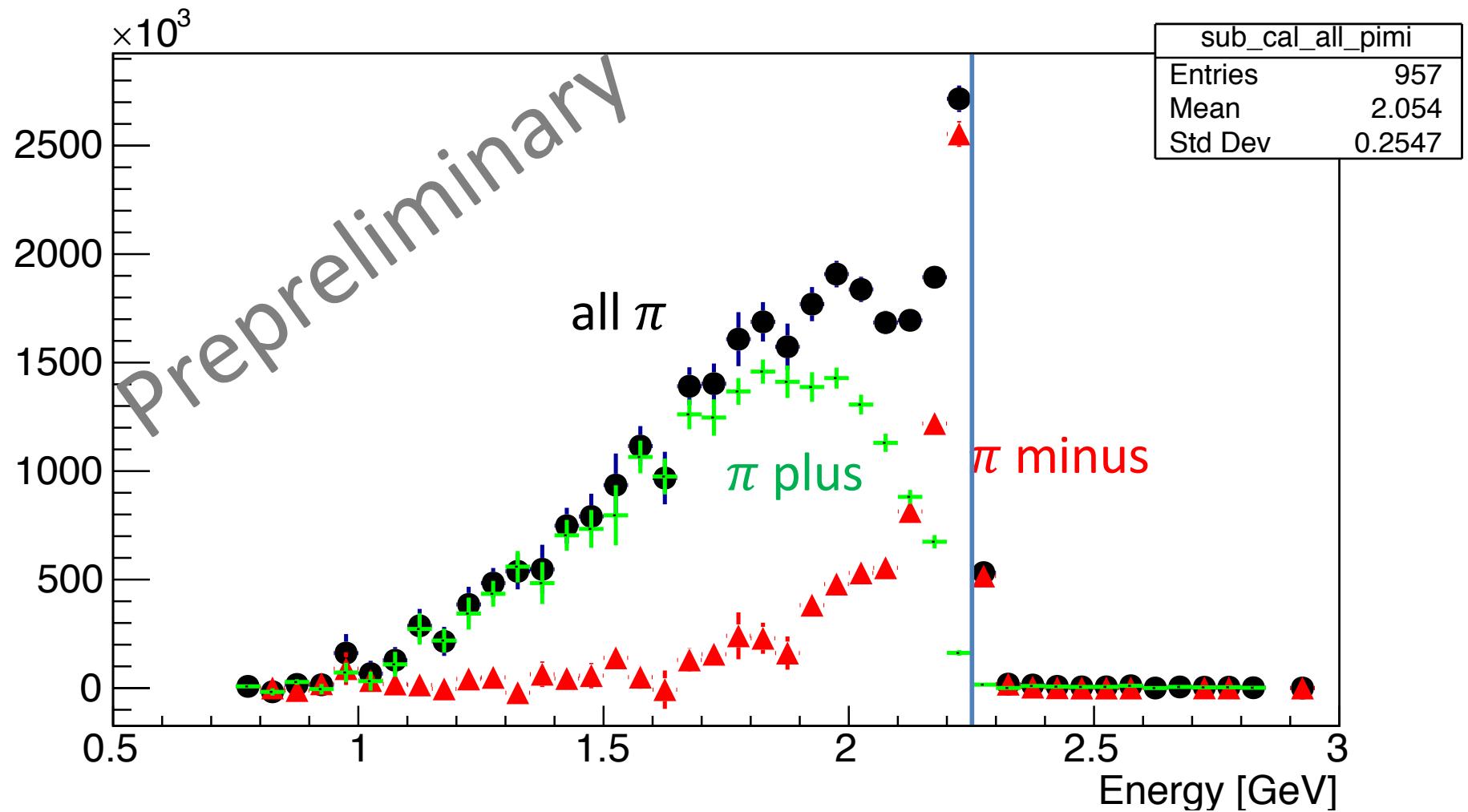
2. Kinematic (e and π only),

- assumes single missing proton

3. Calorimetric: $E = E'_e + E_\pi + T_p + \epsilon$

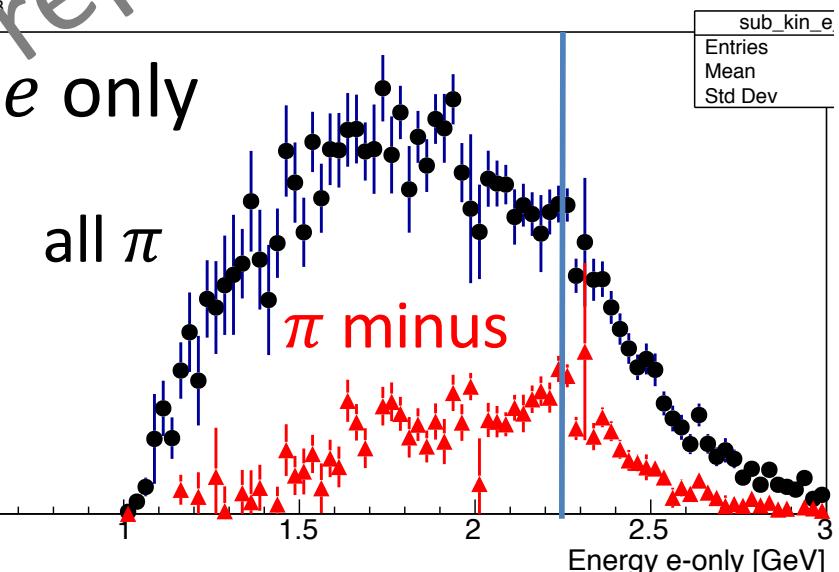
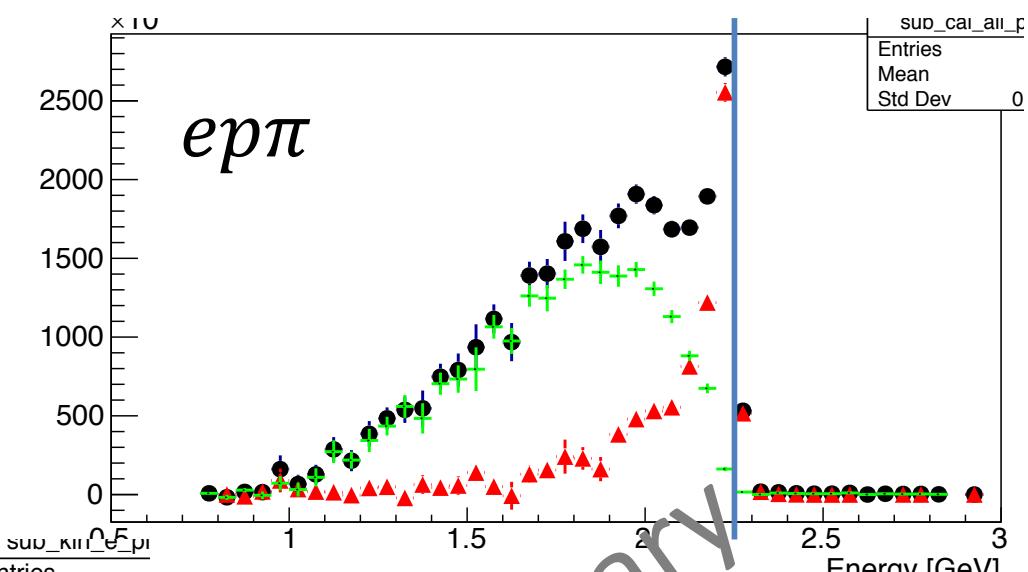
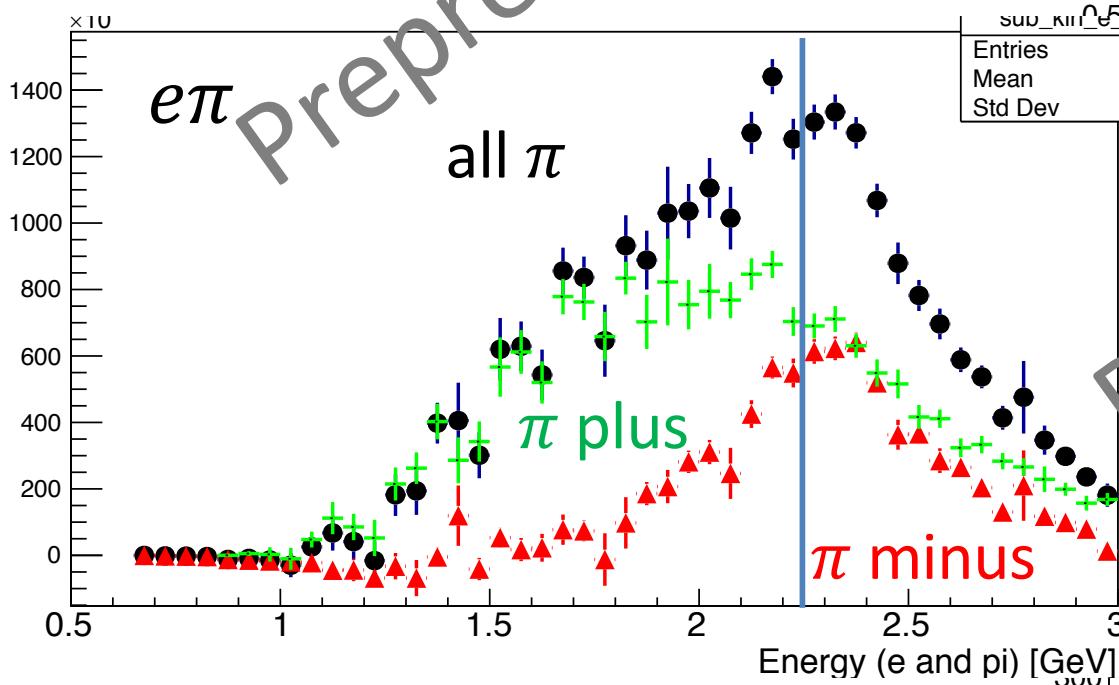
Comparisons to GENIE coming soon ...

$C(e,e'p\pi)$ 2.2 GeV



$C(e,e'p\pi)$ 2.2 GeV

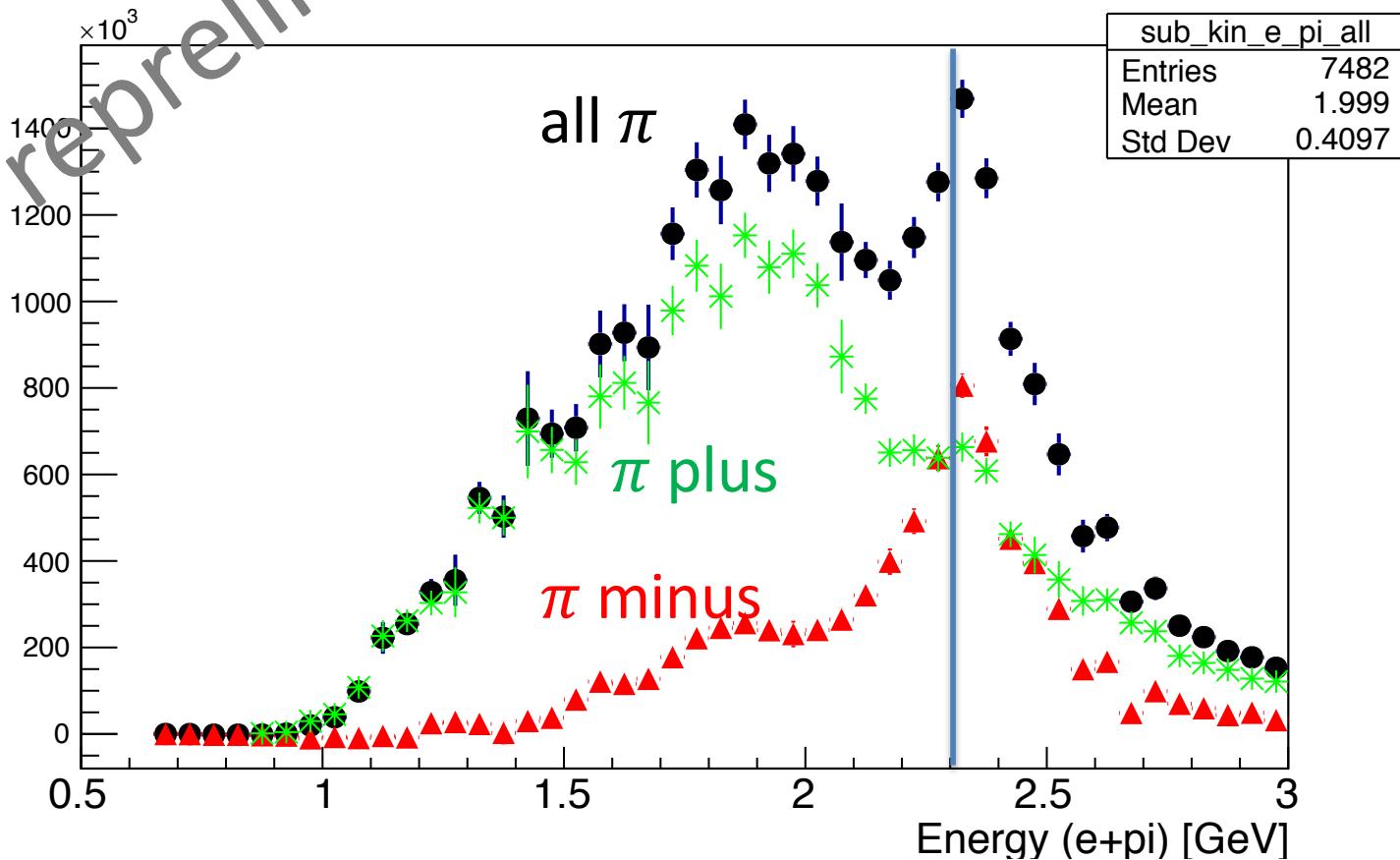
Prepreliminary



More resonances?

3He (e,e'p π) 2.2 GeV
one pion channel
 $e + \pi$ energy

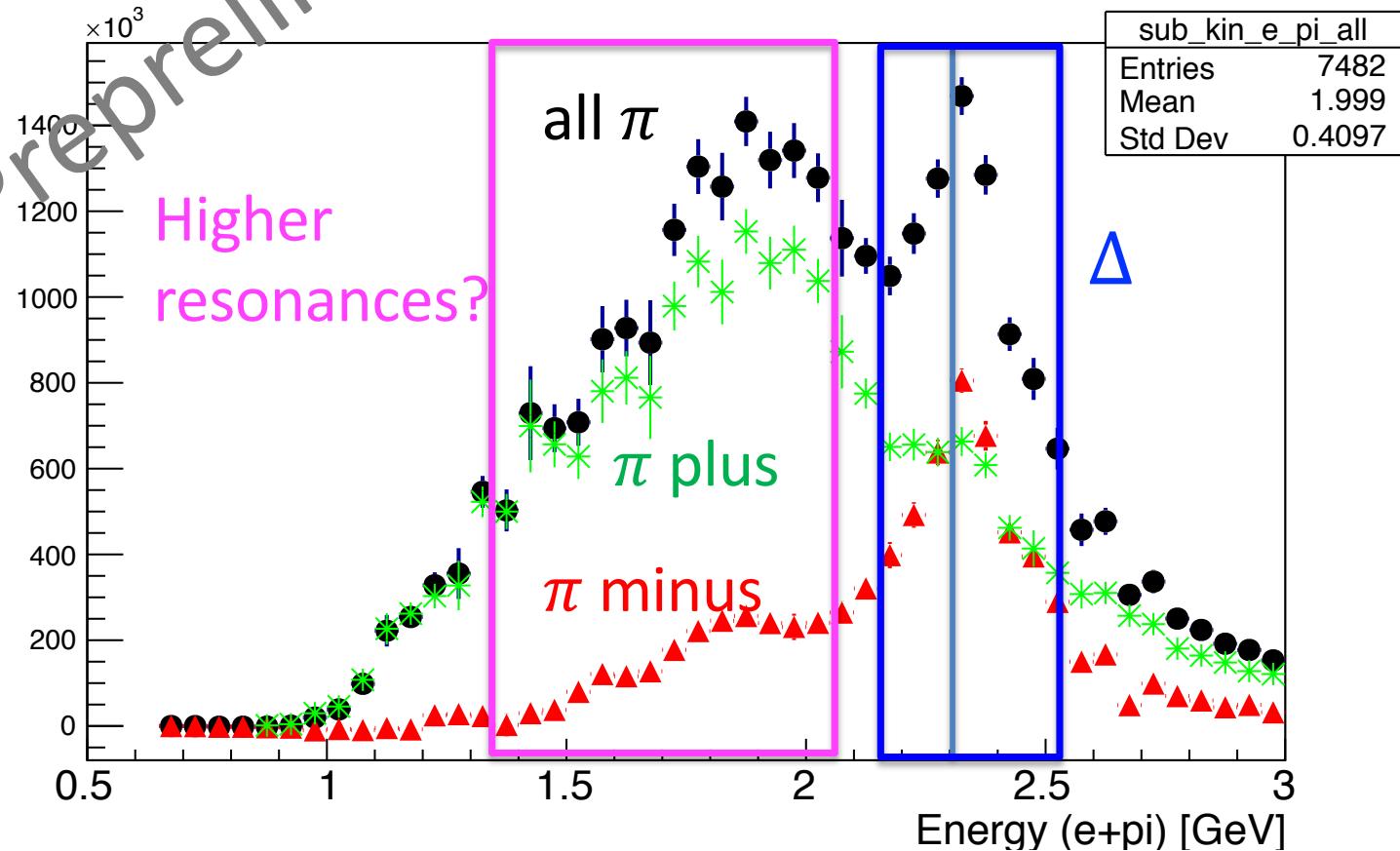
Pre-preliminary

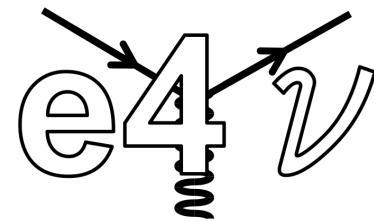


More resonances?

3He (e,e'p π) 2.2 GeV
one pion channel
 $e + \pi$ energy

Prepreliminary

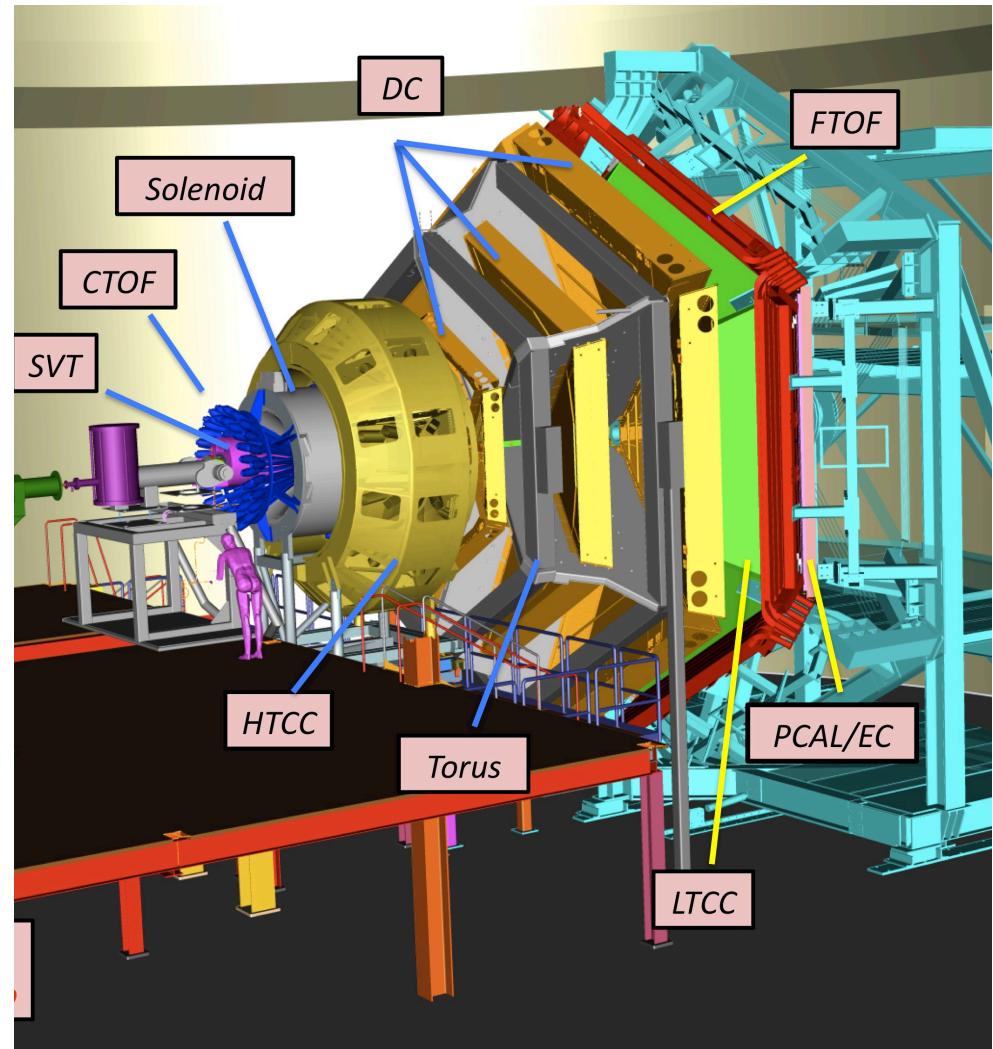


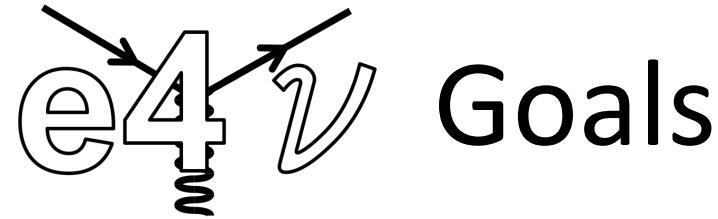


CLAS12

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- forward detector ($5 - 40^\circ$)
 - Toroidal magnetic field
 - $\frac{\delta p}{p} \sim 0.5 - 1\%$
 - Neutrons:
 - 50% effi for $p > 1 \text{ GeV}/c$
 - $\frac{\delta p}{p} \sim 10 - 15\%$ for $1 \text{ GeV}/c$
- Hermetic central detector ($40 - 135^\circ$)
 - 5 T solenoidal field
 - Neutron effi $\sim 10 - 15\%$
 - Neutron $\frac{\delta p}{p}$: 60 ps @ 0.3 m
- 45 beam days **approved** with an **A rating** for
 - 1.1, 2.2, 4.4, and 6.6 GeV beam energies
 - d, He, C, O, Ar, Sn and SRC targets

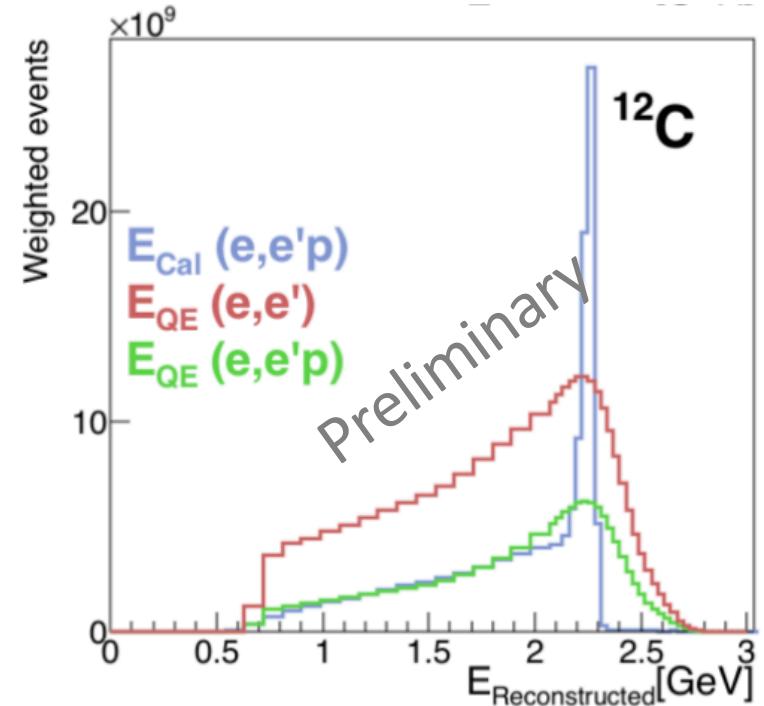




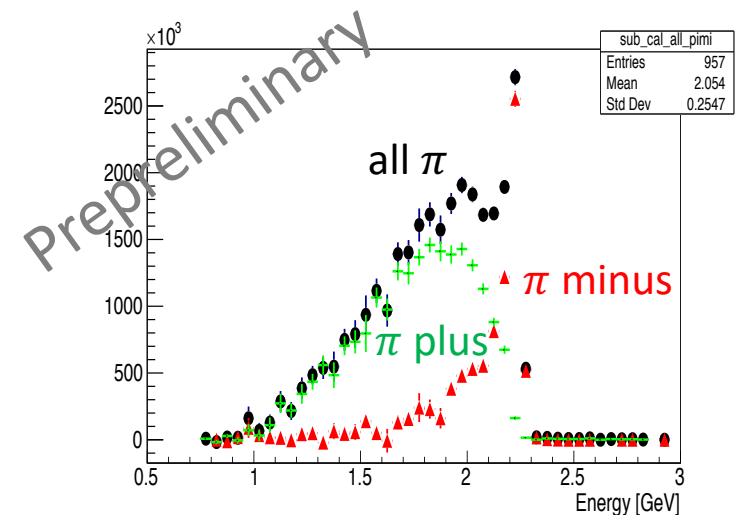
- We provide event yields and detector acceptance maps
 - Many beam energies
 - Many targets
 - Many event topologies
- Let experts use these to tune generators and understand energy reconstruction
- **What do you want from the data?**



- Nuclear physics is complicated!
- Electron scattering can contribute dramatically to neutrino experiments
 - Similar physics
 - Lots of data available
 - Lots more to come
- Neutrino community input is welcome



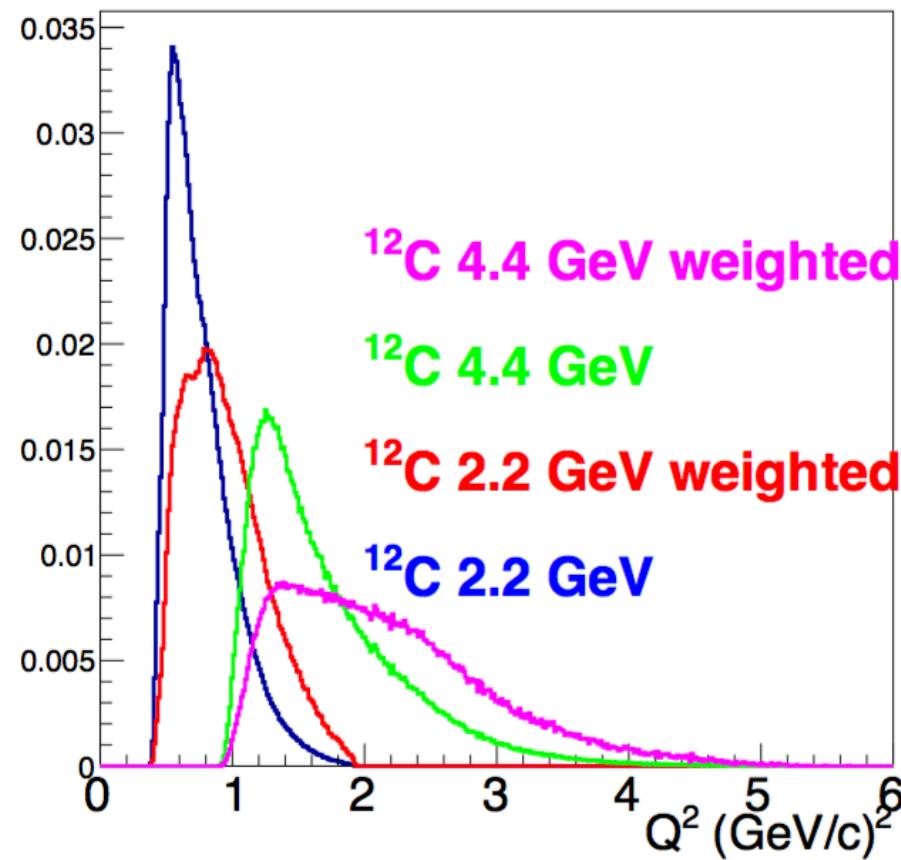
Zero pion channel



One pion channel

Backup slides

Mott weighting



Similarity of electron and neutrino GENIE

2.2 GeV Fe, zero-pion. QE

